Joel Adam Gordon

TOWARDS A UNIFIED THEORY OF DOMESTIC HYDROGEN ACCEPTANCE: A MIXED-METHODS MULTIGROUP ANALYSIS

Cranfield University
School of Water, Energy and Environment
PhD in Energy

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Academic Year: 2023-2024

Supervisor: Prof. Nazmiye Ozkan
Associate Supervisor: Dr. Ali Nabavi
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

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ACADEMIC INTEGRITY DECLARATION

I declare that:

- the thesis submitted has been written by me alone.
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- all content, including primary and/or secondary data, is true to the best of my knowledge.
- all quotations and references have been duly acknowledged according to the requirements of academic research.

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ABSTRACT

The historical record reflects the need to understand the dynamics of social acceptance in advance of technology deployment to minimise the risk of non-adoption or slow diffusion. In the emerging context of hydrogen energy technologies, research on social acceptance has ebbed and flowed, reflecting various hype cycles associated with the hydrogen economy. Following primary interest in public perceptions of hydrogen for transport applications, a social science research agenda on hydrogen energy technologies for domestic space and hot water heating, and cooking has recently emerged. Research uptake follows growing policy interest in converting the national gas grid to hydrogen in countries such as the United Kingdom. The question remains, how do existing gas users in the United Kingdom perceive the prospect of switching to a hydrogen home? In response, this thesis advances a unified theory and establishes a comprehensive typology of domestic hydrogen acceptance, which embed multiple dimensions such as knowledge and awareness, environmental attitude, and financial perceptions. Partial least squares structural equation modelling is employed to determine the antecedents of domestic hydrogen acceptance and adoption intention, which include perceived community benefits, perceptions of hydrogen production pathways, public trust, and positive emotions. Subsequently, partial least squares multigroup analysis is applied to explore the potential for divergent consumer perceptions and preferences. Notably, the statistical findings suggest technology perceptions is the main determinant of adoption potential among consumers who are non-engaged in technology and the environment. By contrast, production perceptions and safety perceptions hold the strongest influence among consumers who are at least moderately engaged in technology and the environment. This thesis enriches conceptual and empirical understanding on the dynamics of domestic hydrogen acceptance and adoption in support of securing a socially acceptable transition pathway for residential decarbonisation. Foremost, segment-specific strategies should be embedded into national and regional policy making on the domestic hydrogen transition to steer progress towards realising a net-zero society.

Keywords

Energy transitions, hydrogen homes, consumer perceptions, social acceptance, technology adoption, partial least squares structural equation modelling

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LIST OF PUBLICATIONS

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Hopes and fears for a sustainable energy future: Enter the hydrogen acceptance matrix, International Journal of Hydrogen Energy 60 (2024). 1170–1191.

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LIST OF ABBREVIATIONS

ADPT	Domestic Hydrogen Adoption Potential
AVE	Average Variance Extracted
AWR	Awareness
AWR	Awareness
BLG	Baseline Group
BEVs	Battery electric vehicles
BLR	Boiler Performance
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation, and storage
CO	Carbon monoxide
C-TAM-TPB	Combined TAM and TPB
CMB	Common method bias
CB	Community Benefits
CR	Composite Reliability
CAGR	Compound annual growth rate
CPB	Comprehensive Perceived Benefits
CPC	Comprehensive Perceived Costs
CPR	Comprehensive Perceived Risks
CTAF	Comprehensive Technology Acceptance Framework
CTA	Confirmatory Tetrad Analysis
CAT	Consumer Acceptance Model
CB-SEM	Covariance based structural equation modelling
CA	Cronbach Alpha
CVPAT	Cross-validated predictive ability test
DTPB	Decomposed Theory of Planned Behaviour
DoI	Diffusion of Innovation
DI	Disruptive Impacts
DHA	Domestic Hydrogen Acceptance
DHAM	Domestic Hydrogen Acceptance Model
DIMMA	Dominance in Mixed Methods Assessment
ECG	Electrocardiogram
ER	Emotional Response
EPC	Energy Performance Certificate
EPSRC	Engineering and Physical Sciences Research Council
IoD	English Indices of Deprivation
EP	Environmental Perceptions
EHB	European Hydrogen Backbone
EU	European Union
FP	Financial Perceptions
FSG	Fuel Stressed Group
Fmri	functional Magnetic Resonance Imaging
GDNOs	Gas Distributions Network Operators
GHG	Greenhouse gas
HSE	Health and Safety Executive
HTMT	Heterotrait-monotrait
HOB	Hob Performance

HETs	Hydrogen energy technologies
HFCVs	Hydrogen fuel cell vehicles
HFSs	Hydrogen fuelling stations
H2-ACPT	Domestic Hydrogen Acceptance
IMPA	Importance-performance map analysis
IS	Information System
IT	Information Technology
IBM	Integrated Behavioural Model
IM	Integrative Model
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
KNW	Knowledge
K-W	Kruskal-Wallis
LV	Latent variable
MIS	Management Information Systems
MAE	Mean absolute error
MICOM	Measurement Invariance Assessment
CH4	Methane
MEG	Moderately Engaged Group
MM	Motivational Model
MGA	Multigroup analysis
NA	Negative Affect
NE	Negative Emotions
NAM	Norm Activation Model
OK	Objective knowledge
Ofgem	Office of Gas and Electricity Markets
ANOVA	One-way analysis of variance
PLS-MGA	Partial least squares multigroup analysis
PLS-SEM	Partial least squares structural equational modelling
PBC	Perceived behavioural control
PC	Perceived Costs
PEOU	Perceived ease of use
PU	Perceived usefulness
PA	Positive Affect
PE	Positive Emotions
PP	Production Perceptions
PAT	Public Attitudes Tracker
PT	Public Trust
RA-H2	Realised Adoption of Domestic Hydrogen
RT	Rational Thought
RET	Renewable Energy Technology
RMSE	Root mean square error
SP	Safety Perceptions
STEEP	Safety-Technological-Economic-Environmental Perspectives
SA	Social Acceptance
SCT	Social Cognitive Theory
SRT	Social Representation Theory
ST	Social Trust
SMR	Steam Methane Reformation
SEM	Structural equation modelling

SEMs	Structural equation models
SK	Subjective Knowledge
SETA	Sustainable Energy Technology Acceptance
SLR	Systematic Literature Review
TP	Technological Perceptions
TAM	Technology Acceptance Model
TAS	Technology Affect Scale
TIS	Technology innovation systems
TPB	Theory of Planned Behaviour
TRA	Theory of Reasoned Action
TSA	Triangle of Social Acceptance
UTAUT	Unified Theory of Acceptance and Use of Technology
UK	United Kingdom
US	United States
VAM	Value-based Adoption Model
VBN	Value-Belief-Norm
VICE	Value-Innovation-Congruence
VIF	Variance inflation factor
VEG	Very Engaged Group
WTA-H2	Willingness to Adopt Domestic Hydrogen
5D-DHAF	Five Dimensions of Domestic Hydrogen Acceptance Framework
ρ A	rho_a

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1 INTRODUCTION

1.1 Background and motivation

Accelerated and sustained global deployment of low-carbon energy technologies is increasingly needed to support climate change mitigation [1–3] and fulfilment of net-zero targets [4]. A critical aspect of the global energy transformation [5,6] involves curbing carbon emissions from the residential sector [7,8]. What is called for is 'deep' decarbonisation[1] [9,10], as opposed to marginal emissions reduction [11]; if ambitions for net-zero buildings [12,13] are to be realised in countries such as the United Kingdom (UK) [14,15].

The historical record shows that achieving rapid energy transitions for the residential sector is feasible, as evidenced by the large-scale uptake of district heating in Denmark [16], solar thermal systems in China [17], and heat pumps [18] in countries such as Sweden [19] and Finland [20]. A notable example of an accelerated national energy transition is also reflected by the switch from manufactured 'town gas'[2] to natural gas in the UK [21,22], which can be traced to 1960–1977 [16].[3] Critically, accelerated transitions can occur in different types of energy markets, whether state-controlled or more open and competitive [16]. For example, "the United Kingdom coordinated a nationalised Gas Council and Area Boards with industry groups, appliance manufacturers, installers and marketing campaigns so that gas central heating reached almost half of all homes" [16].

More than four decades later, UK policy makers are targeting a residential energy transition, wherein natural gas appliances should be replaced by alternative low-carbon energy technologies [23,24]. As specified in the Heat and Buildings Strategy (October 2021) [23], the government aims to phase out the installation of both new and replacement gas boilers by 2035, alongside other fossil-fuel heating technologies [25]. As examined within this thesis, the envisioned transition may include a potential

[1] Researchers link 'deep' decarbonisation [329] to meeting recommendations set by the Intergovernmental Panel on Climate Change (IPCC), which specify limiting global warming to 1.5°C will require a peak before 2025, reducing emissions by 43% by 2030, 60% by 2035 and reaching net-zero in early 2050 [330,331].

[2] Composed of a mix of methane (CH4), carbon monoxide (CO) and up to 50% hydrogen [30].

[3] Scholars acknowledge and debate the difficulty of tracing the formative phase of energy transitions when formalising national case studies [31,32]. For example, Arapostathis et al. [22] discuss the transition from town gas to natural gas for the period 1948–1977.

role for ‘hydrogen homes’, composed of hydrogen-fuelled appliances for domestic space heating, hot water, and cooking [26–28].

Notably, the UK Hydrogen Strategy [24], released in August 2021, committed to a scaling up of trials and demonstration for hydrogen homes, while the British Energy Security Strategy (April 2022) [29] doubled the 2030 hydrogen production target to 10 GW, of which at least 50% should be electrolytic ‘green’ hydrogen, alongside carbon capture, utilisation, and storage (CCUS-)-enabled ‘blue’ hydrogen [24]. However, a prerequisite for deploying hydrogen homes [30] is social acceptance [31,32]. This reality is reflected by the collapse of a planned hydrogen villages in the North of England; firstly, in Whitby village (Ellesmere Port, Northwest England) during July 2023 [33,34], and subsequently in Redcar (Yorkshire, Northeast England) during December 2023 [35,36].[4]

Reflecting on the configuration of past, ongoing, and emerging national energy transitions [31,37–39], social acceptance [40–42] – understood as a complex, multi-actor and cross-scalar phenomenon [43–45] where the ‘positions’ of respective actors are dynamic and continuously evolving [46] – constitutes a precondition for the rapid diffusion of low-carbon energy technologies [44,47,48]. Historically, social acceptance scholarship has focused on socio-political, market, and community acceptance dimensions [49] to reflect people’s response to renewable energy technologies [42]. However, in the context of domestic energy adoption [50], it is imperative to include a direct research focus on attitudinal and behavioural acceptance to better understand consumer perceptions, attitudes, motivations, and preferences [51–54].

Notably, the need for a multi-dimensional research lens in broader technology acceptance research has been recognised since at least the 1980s: “the social acceptability of large-scale technologies depends upon a wide range of things, some related to safety and economics, but also some factors of cultural, social, and psychological significance” [55]. Nevertheless, both the technology acceptance[5] [56–58] and energy acceptance literatures [59–62] reflect only partial progress towards

[4] The Whitby area is managed by Cadent Gas, while Redcar is managed by Northern Gas Networks.
[5] Throughout this thesis, the broader ‘technology acceptance’ literature (excluding energy-focused studies) refers principally to studies on computer-orientated products and services, vis-à-vis the Technology Acceptance Model (TAM) [156] and subsequent contributions to the literature [56,334], which are discussed in Chapter 2.

developing integrated conceptual frameworks, which can be rigorously tested through quantitative techniques such as structural equation models (SEMs) [63–66].

In the context of hydrogen energy transitions, a "new social science research agenda" is needed to account for the dynamics of social acceptance [67]. At present, the literature is characterised by an underlying deficit in terms of theoretical and empirical engagement [68,69]. Notably, in the early 2010s, Huijts [70] critiqued the inconsistent use of terminology within the hydrogen acceptance literature, while highlighting a tendency towards representing psychological variables with a single measurement item, which undermines reliability and validity in quantitative analyses. More recently, Scovell [69] further underscored inconsistencies regarding the measurement of psychological constructs, alongside a lack of clarity regarding how "context-specific beliefs" shape consumer attitudes towards hydrogen energy technologies.

To date, research groups have focused mostly on the acceptance of hydrogen fuel cell vehicles (HFCVs) and hydrogen fuelling stations (HFSs) [68,69], while applications for residential energy use [27] have received scarce attention [71,72]. Notably, emergent research on domestic hydrogen acceptance is largely constrained to relatively few studies on datasets collected in Australia [73,74], the UK [27,67], and parts of Europe [71,72].

Against this background, this thesis engages with the development of a national hydrogen economy in the UK context [23,24,75] and specifically the prospective transition to hydrogen homes. With around 21.2 million gas appliances and 12.7 million gas cookers installed across the UK housing stock [28,76] – accounting for around 16% of total UK carbon emissions (mostly from heating)[6] [77] – converting the gas grid to supply parts of the housing stock with low-carbon hydrogen [78–80] may prove critical to supporting net-zero ambitions [14,81,82]:

> "Hydrogen technologies can play an important role in decarbonising our energy system in a variety of ways across the energy value chain. It is therefore critical to identify the strategic roles as well as the conditions under which hydrogen energy systems become attractive for the energy transition" [83].

[6] Cooking accounts for around 2% of total UK carbon emissions, compared to around 14% for domestic heating, most of which is attributed to gas boilers [77] However, the emissions from cooking are embedded in the networks, institutions, and infrastructure of the wider energy system [335].

This research is predicated on the notion that technical change is “an irremediably social process” [84], wherein the speed, scope, and direction of the energy transition [85,86] is shaped by the co-evolution of technology and society [87]. In view of the current research gap, a critical question arises regarding the potential configuration of social acceptance for hydrogen homes, stimulating several points of related inquiry: Under what conditions would local communities support government plans for domestic hydrogen trials? How likely are existing gas users to welcome a switch to hydrogen appliances? Will hydrogen heating and cooking technologies generate similar or different consumer perceptions? To what extent will prospects for transitioning to hydrogen homes be viewed differently across parts of society?

Ahead of the UK government taking a strategic decision on role of domestic hydrogen by 2026, this thesis is motivated by the need to understand the dynamics of social acceptance and adoption potential during the formative stage of the transition. Comprehending these dynamics is integral to supporting residential decarbonisation pathways which are socially acceptable. Through consumer-orientated, mixed-methods analysis, this thesis supports the UK government’s call for “research to understand consumer acceptability and behaviour” [88] to safeguard against the risk of “socially rejected energy-transition pathways” [89].

The remainder of this introduction is structured as follows. Section 1.2 states the aim and objectives of the thesis, while Section 1.3 provides an overview of the PhD project and research design. Next, Section 1.4 highlights the intended contribution and details the links between research phases and outputs. Section 1.5 describes the research epistemology, while Section 1.6 outlines the chapters composing this thesis. Finally, Section 1.7 reports the materials that have been disseminated during the project, which included several publications in peer-reviewed journals. Importantly, Section 1.3 and Section 1.4 outline the totality of the PhD project, including all materials included in Appendices, whereas Section 1.6 specifies the chapters which make up the main body of the thesis.

1.2 Aims and objectives

This PhD thesis engages with residential decarbonisation in the UK context, with the motivation to better establish the antecedents of domestic hydrogen acceptance and adoption potential, in addition to identifying the factors which explain heterogeneous

attitudes and perceptions among consumers. Through this dual focus, the research aims to inform consumer engagement strategies, deployment pathways, and policy making to strengthen opportunities for enacting a socially acceptable transition to hydrogen homes in the UK. Four distinct objectives contribute to the underlying motivation and aim of the thesis:

1. Develop a conceptual framework to examine the dynamics of domestic hydrogen acceptance and adoption intention.
2. Establish an empirically-grounded typology of domestic hydrogen acceptance and determine the factors which explain consumer heterogeneity.
3. Construct and validate a structural equation model to determine the salient predictors of domestic hydrogen acceptance across the UK population.
4. Construct and validate a structural equation model to determine the salient predictors of domestic hydrogen adoption potential across sub-groups of the UK population.

1.3 Overview of research development and design

This PhD project was supported by funding from the Engineering and Physical Sciences Research Council (EPSRC),[7] with co-sponsorship from Cadent Gas Limited. At the time of conception, the use of mixed-methods research was planned (i.e. 'fixed'), however, the implemented methods proved 'emergent' in respect to selecting specific qualitative and quantitative approaches as the project evolved [90]. For example, the decision to conduct online focus groups was taken partly in response to COVID-19, while preliminary research plans for the final phase of the project (i.e. deliberative workshops and stakeholder interviews) were suspended due to the extensive data collected via the online survey, which presented several emerging opportunities for data analysis. Specifically, responses at the end of the online survey yielded a relatively high response rate (N = 1213, ~65.7%).[8] Respondents were given the following instruction:

Please use this text box to explain more about your attitudes towards hydrogen or any other reflections on this topic.

[7] Grant number EP/T518104/1.
[8] Of which 1064 responses were drawn upon for the analysis presented in Chapter 3.

Foremost, research funding was allocated towards conducting online focus groups between February and April 2022 (see Section 1.4.2) and an online survey between October and December 2022 (see Section 1.4.4), in conjunction with research training and participation in conferences (see Section 1.7.3).

The project was realised through four distinct research phases as further described in Section 1.4. Throughout all phases of the project, research methods adhered to the strictest standards of ethical compliance and data protection. As illustrated in Fig. 1-2, the overall research design aligns broadly to an exploratory, sequential mixed-methods approach [91,92], whereby online focus groups precede the online survey (i.e. QUAL → QUANT). Similarly, Kumar et al. [93] employed focus group interviews (N = 57) before conducting a large sample survey and carrying out multi-group analysis to examine student perspectives towards culturally-sensitive curriculars.[9]

Notably, when examining consumer attitudes towards green electricity in the UK, Ozaki [94] conducted two focus groups (N = 12) ahead of a survey study (N = 103), which was supplemented by semi-structured interviews (N = 10) in the final research stage (i.e. QUAL → QUANT → QUAL). Additionally, in view of the general paucity of studies on consumers' intention to adopt smart meters, Wunderlich and Veit [95] employed a mixed-methods multistrand design, through in-person interviews with current and potential early adopters (N= 24), followed by an online survey with German citizens responsible for energy decisions in their household (N = 930). Nevertheless, it should be acknowledged that in other contexts, an explanatory, sequential mixed-methods approach (i.e. QUANT → QUAL) may prove more suitable. For example, Renaud and Van Biljon [96] verified quantitative findings through structured interviews with senior mobile phone users to develop the Senior Technology Acceptance and Adoption Model for Mobile technology (STAM).

1.3.1 At the intersection of mixed methods research

While studies grounded in wholly qualitative approaches or purely quantitative methods have their respective advantages and use cases [97–100], this thesis contends that a mixed-methods research approach is best aligned to examining technology perceptions during the formative phase of the hydrogen transition. The

[9] The example is noteworthy in sharing a similar sample for the focus groups phase (i.e. N = 57 compared to N= 58), and for conducting multigroup structural equation modelling.

research perspective aligns with the notion that mixed methods research can leverage synergies from different paradigms [101]. At the same time, this PhD project was undertaken in a similar spirit as recently expressed by Brown et al. [102], following their commentary on the "methodological intersections between realist inquiry and structural equation modelling":

> "We would stress that there is no apparent superordinate model of combining the two methodologies or any one approach that we see as intrinsically superior or of greater value than any other. Rather, different combinations of the two methodologies have the potential to be used to achieve different ends."

Specifically, this thesis demonstrates the efficacy of integrating qualitatively-driven research methods alongside PLS-SEM. Documenting the paucity of studies which present PLS-SEM within a mixed methods research design [102], Kurtaliqi et al. [103] recently advocated for an "advanced mixed methods approach," whereby PLS-SEM is supported by a qualitative pre-study and post-study. Notably, an exploratory study in the context of consumer behaviour, as derived in this PhD via online focus groups, can yield "relevant contingent concepts" which can be quantitatively tested via PLS-SEM [103]. Optimally, a final qualitative study can offer more fine-grained, descriptive insights on the focal topic and enrich findings from PLS-SEM [103], as was approximated in this thesis by securing written responses from survey participants.

Consequently, this thesis implements a dynamic approach to mixed-methods analysis by interrelating and adapting multiple research components [90,104], as opposed to selecting a specific design from an available typology [105,106]. Additionally, the approach proved highly synergistic whereby the interactions between respective research strands [107,108], both within and between specific chapters, exceeded the sum of individual qualitative or quantitative contributions [109].

Following the inception of the PhD in October 2021, several rounds of initial literature review, theoretical exploration, and conceptual development were carried out (see Appendix A–C), ahead of primary data collection. The second research phase involved conducting a series of online focus groups between February and April 2022, which provided scope for mixed-methods data analysis across different components of the evidence base (see Appendix D–F). During this stage of the project, it emerged that a more extensive evidence base was required to advance a unified theory of domestic hydrogen acceptance, in line with the first research objective. In response, the third

research phase was dedicated to this goal, which involved conducting an integrative, comparative literature review on hydrogen and domestic energy acceptance.

As a result, the fourth and final research phase is guided by a comprehensive conceptual framework; aligning to the notion of a transformative research design, which sees the theoretical perspective inform the analytical approach [110–112]. In parallel, the analysis performed during the second research phase (i.e. online focus groups) provided the foundations for undertaking hybrid deductive-inductive coding (see Chapter 3 and Appendix G), alongside partial least squares structural equation modelling (PLS-SEM) and (PLS) multigroup analysis in Chapters 4 and 5, respectively. By incorporating PLS-MGA, the thesis leverages opportunities to triangulate the results with mixed-methods insights gathered in earlier research outputs (see Appendix D–F), in addition findings in the literature. Overall, the PhD project advances a mixed-methods research approach [90,103,113], which leverages the exploratory sequential approach as a mechanism for informing the online survey design.

Critically, the chapters composing the thesis correspond to the third and fourth research phases exclusively.[10] As a result, this configuration shifts the research methods represented within the body of the thesis towards a mixed-methods convergent design, since the qualitatively-driven outputs are excluded (see Appendix D–E). Accordingly, the empirical focus centres on a single dataset[11] retrieved via the online survey (N = 1845). However, this more recent and extensive evidence base presented opportunities for employing different analytical techniques, namely thematic coding and structural equation modelling (SEM). Nevertheless, it should be acknowledged that the deductive quantitative paradigm is the dominant approach within this thesis [106], since PLS-SEM is represented in two consecutive chapters.[12]

In sum, the second research stage composing this PhD project was characterised by an inductive approach via thematic coding of data from online focus groups, while the third phase entailed coding two datasets to support an integrative, comparative review of hydrogen and domestic energy studies. By contrast, the fourth stage was guided by an abductive approach [114] in developing an empirically-grounded typology via hybrid

[10] The structure adheres to the convention of including up to five empirical chapters within a PhD thesis.
[11] Analysis conducted on a single dataset is still identified as mixed methods since different research approaches with specific features supports mutual enrichment between findings, which would not be achieved if using a single method [103].
[12] The thesis thus falls within the realm of ‘dominant less dominant design’ [95].

deductive-inductive coding, whereas a strictly deductive approach was adhered to when implementing PLS-SEM. Thus, the final research stage – corresponding to Chapters 3 to 5 in this thesis – followed a convergent, mixed methods design involving abduction and deduction.

The interconnections between project phases and research outputs are illustrated via Fig. 1-1.[13] to reflect the workflow and underlying rationale of each stage. In Fig. 1-1, dark blue boxes correspond to outputs from the first research phase, while light blue boxes represent the second research phase. The third phase is captured within a green box, which is bordered by light and dark blue boxes to emphasise the integration between research phases. Lastly, the final research phase is represented by dark green boxes.

In Fig. 1-1, single headed black arrows are included to show direct links between research outputs, as reflected within the initial phase (dark blue boxes), as well as between the final manuscripts (dark green boxes). By contrast, double-headed grey arrows show the bi-directional link between outputs from online focus groups (light blue boxes), as well between two publications in the final research phase. Accordingly, light blues lines and dark green lines reflect the sequential, exploratory nature of the research, which was bridged by a systematic literature review.

Accordingly, the methodology reflects the process outlined by Tashakkori and Creswell [115] in the inaugural volume of the Journal of Mixed Methods Research:

> "…the investigator collects and analyses data, integrates findings, and draws inferences using both qualitative and quantitative approaches or methods in a single study or program of inquiry."

In sum, the focus is on developing a cohesive narrative, as qualitative and quantitative strands come into conversion with one another [104,116]. As a result, this thesis seeks fertilisation between research techniques [117]; acknowledging the observation of Walker and Baxter [118] vis-à-vis their Dominance in Mixed Methods Assessment (DIMMA) model, which documented the marginalisation of qualitative methods in studies on wind energy acceptance. The next sub-section outlines the four research stages composing the PhD project, thereby detailing the specific links between the

[13] Throughout this thesis, all figures are the author's own design unless otherwise stated.

underlying methodological approach and research paradigm, which are visualised in Fig. 1-2.

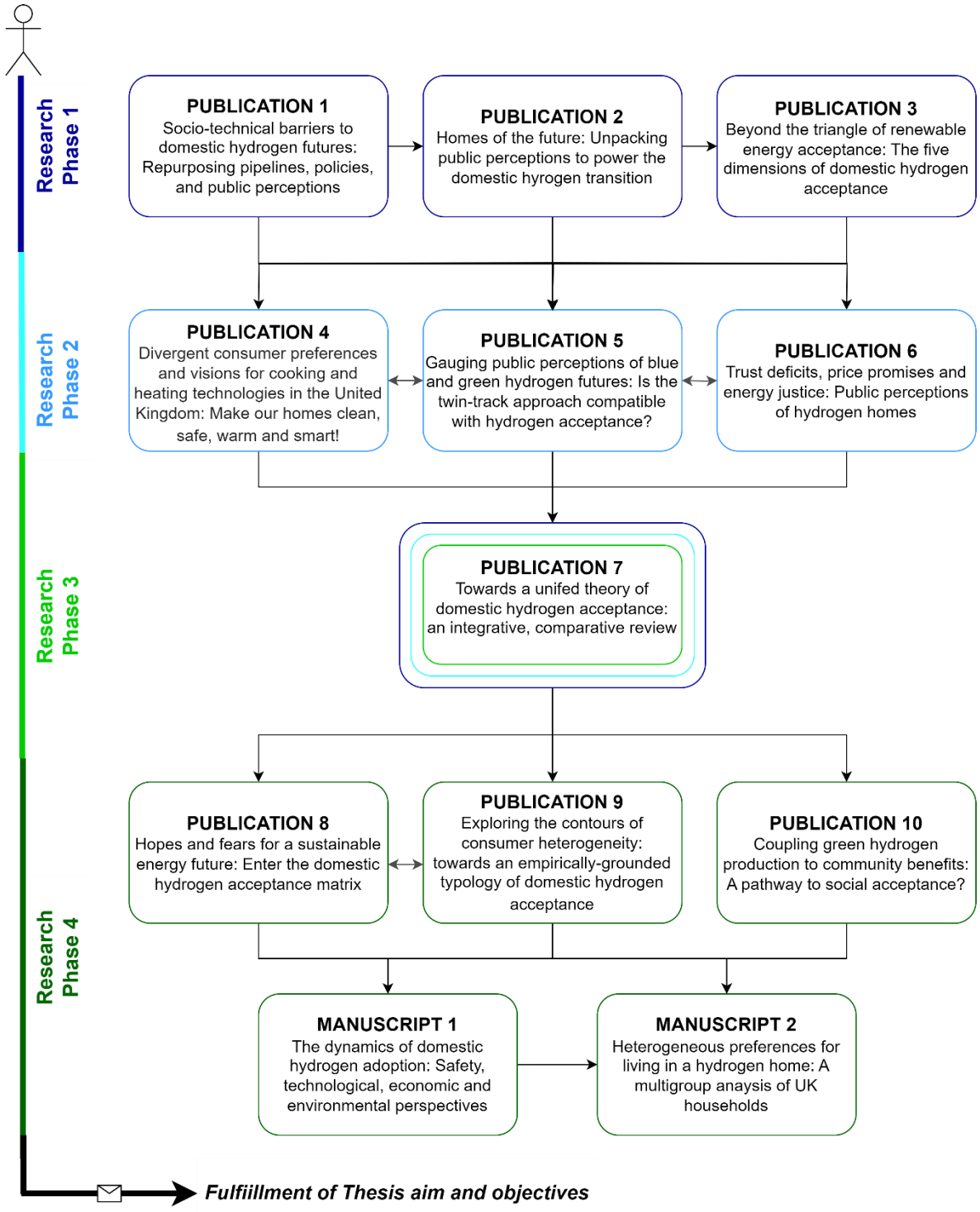

Fig. 1-1. Interconnections between project phases and research outputs.

Dark blue = Research Phase 1; Light blue = Research Phase 2; Green = Research Phase 3; Dark green = Research Phase 4. Single-headed arrows = direct links (i.e. sequential analyses); Double-headed arrows = bi-directional links (i.e. convergent analyses)

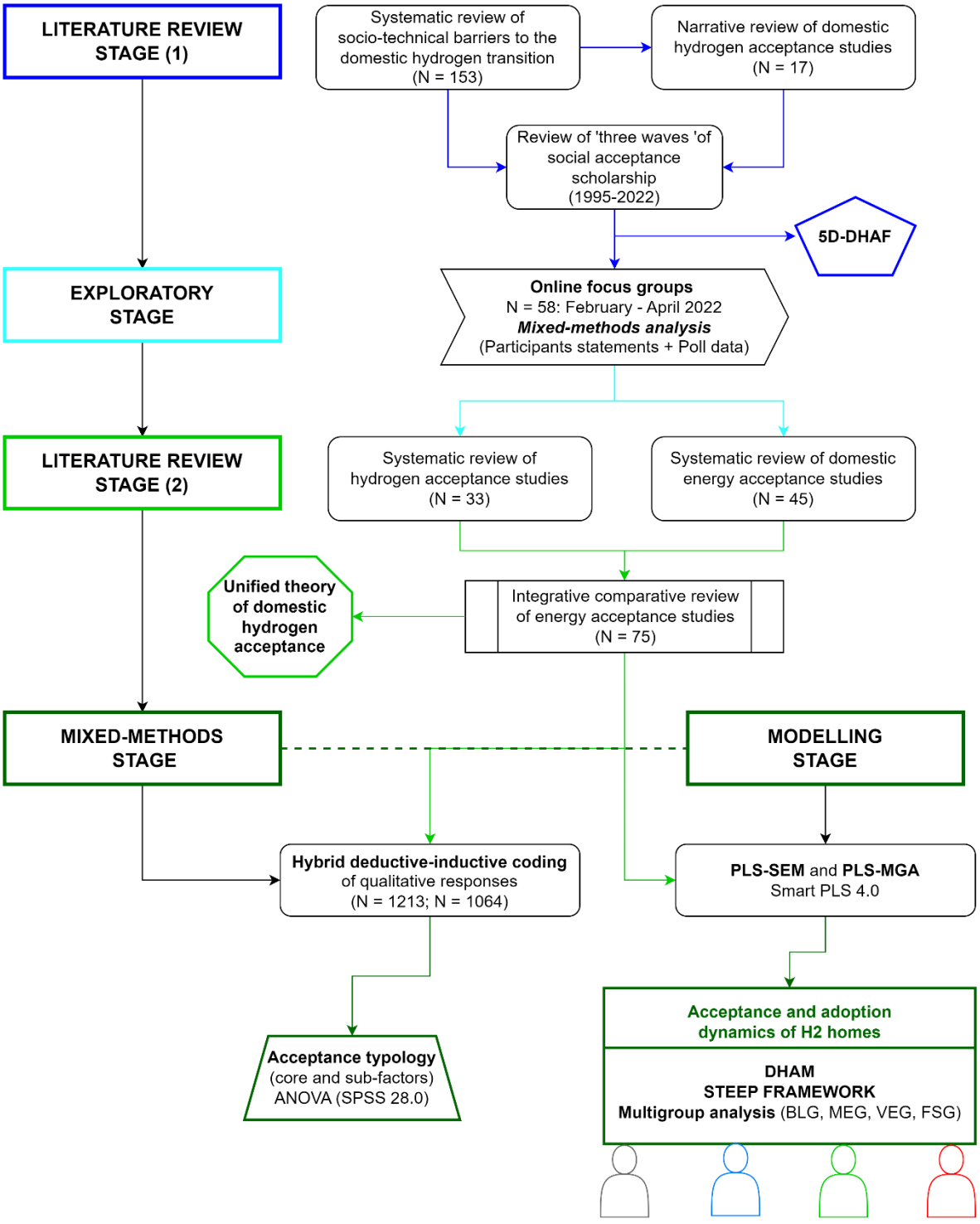

Fig. 1-2. Overview of research stages and methods.

5D-DHAF: Five Dimensions of Domestic Hydrogen Acceptance; PLS-SEM = Partial least squares structural equation modelling; PLS-MGA = Partial least squares multigroup analysis; DHAM = Domestic Hydrogen Acceptance Model; STEEP = Safety-Technological-Economic-Environmental Perspectives; BLG = Baseline Group (Grey); MEG = Moderately technology and environmentally Engaged Group (Blue); VEG = Very technology and environmentally Engaged Group (Green); FSG = Fuel Stressed Group (Red).

1.4 Linkages and synergies between project outputs

This thesis seeks to advance critical understanding and fundamental knowledge on the dynamics of domestic hydrogen acceptance and adoption potential. Accordingly, the analysis targets specific conceptual and empirical contributions in line with best practices for the social sciences [119]. In doing so, this research internalises the criteria proposed within “Pasteur’s Quadrant” of transformative research [120], seeking critical insights to address pressing energy, environmental, and social challenges [119,121]. To achieve the stated objectives of the project, several manuscripts were submitted to energy research journals, leading to publication or ongoing peer review, as outlined in Fig. 1-1. The following sub-sections contextualise the interconnections between project phases and research outputs, as illustrated in Fig. 1-2.

1.4.1 Research Phase 1: The five dimensions of domestic hydrogen acceptance

During the first research phase, results translated into one conference paper and three peer-reviewed journal publications. The first publication makes an original contribution by developing a socio-technical transitions systems framework for evaluating barriers to the domestic hydrogen transition (Publication 1: Appendix A). The work expands on prior contributions such as Cherp et al.’s [86] meta-theoretical framework on energy transitions which integrated techno-economic, socio-technical, and political perspectives. Instead, the analysis unbundles and extends the ‘three perspectives’ into respective techno-economic, technical, political, market, and social dimensions. Moreover, the framework explores interactions between these dimensions, examining barriers to low-carbon hydrogen production, cost factors, safety, sustained political support, technology development, market growth, and social acceptance. The article concludes by underlining the need for radically ‘repurposing’ pipelines, policies, and public perceptions to advance prospects for developing national hydrogen economies in countries such as the UK.

The examination of socio-technical barriers to the hydrogen economy, as specified to the case of the UK domestic hydrogen transition, provides the broader context within which to explore social acceptance for hydrogen homes. Within the social dimension, the proposed framework engages with public perceptions of hydrogen safety, environmental impacts, cost factors, behavioural impacts, and equity implications,

thereby providing an entry point into the research domain. Subsequently, a direct link is made to identify the factors influencing domestic hydrogen acceptance based on a narrative literature review of available academic studies and reports (Publication 2: Appendix B).

In view of this evidence base, 14 acceptance factors are identified ranking from 'critical' (2 factors) to 'minor' (1 factor), with 'major' (4), 'significant' (3) and 'moderate' (4) factors composing the full list. Additionally, this article introduces the notion of five distinct hydrogen acceptance dimensions, which correspond to each factor.[14] Notably, the narrative review marks an important juncture in advancing the research domain, since a prior systematic review on the broader hydrogen economy conducted by Emodi et al. [68] retrieved just five studies on domestic hydrogen acceptance for the search period 2008–2020.

With the context mapped and the literature on domestic hydrogen acceptance reviewed, the research proceeded by formalising a multi-dimensional conceptual framework to guide subsequent research exploration (Publication 3: Appendix C). Specifically, the proposed framework extends Wüstenhagen et al.'s "triangle of social acceptance of renewable energy innovation" [49] by integrating attitudinal and behavioural acceptance to the established dimensions of socio-political, market, and community acceptance. In doing so, the Five Dimensions of Domestic Hydrogen Acceptance Framework (5D-DHAF) accounts for the micro-scale where decision-making and behavioural response take place, in addition to macro- and meso-scales. As consolidated throughout the thesis, this distinction is critical to engaging meaningfully with energy acceptance in the residential context, wherein the decisions of individual consumers shape prospects for market growth.

1.4.2 Research Phase 2: Online focus groups analysis

The second phase of the research project was motivated by the need to gather in-depth qualitative insights on the topic, ahead of developing survey instruments for deploying an online questionnaire. As articulated by Memon et al. [122], qualitative methods such as focus groups, participatory-observation, and personal interview are imperative for exploring contextual factors in an emerging research context. In this

[14] For example, 'financial costs' ranks as the most critical factor and corresponds to the 'market acceptance' dimension.

case, the researcher opted for online focus groups, in part due to the constraints imposed by COVID-19 during the planning phase.

In the energy transitions field, the efficacy of focus groups has been demonstrated by studies on emergent research areas [123,124] including hydrogen acceptance [74,125]. The method offers several advantages in social research [100]; supporting exploratory qualitative research, ahead of subsequent quantitative analysis [91,92]. Qualitative methods such as focus groups are also recommended when interested in establishing the scope of potential moderating effects [122].

In this thesis, a focal point included testing whether different configurations of technological and environmental engagement, in addition to socio-economic status (i.e. fuel stressed consumers vs non-fuel stressed), influenced support levels for hydrogen homes. The feasibility of examining these effects via PLS-MGA (see Chapter 5) was grounded in firstly identifying the antecedents of domestic hydrogen acceptance among consumer segments via online focus groups. Specifically, Phase 2 involved conducting ten semi-structured sessions (N = 58), which ran between February 14th and April 6th, 2022, and were carried out in Zoom. Notably, the format supported the inclusion of (Zoom) polls to extract additional data.

In summary, focus groups offer an efficient and reliable method for exploring perspectives on underexplored topics, wherein the format enables participants to establish “new insights and priorities” [123], while the researcher aims to identify areas of convergence and divergence between responses [126,127]. Although Phase 2 was primarily qualitatively-driven [128], it also included an embedded, convergent analytical approach through examining multiple strands of qualitative and quantitative data [90,92,129]. Additionally, throughout all stages of the focus groups analysis, a combination of content analysis [130,131], thematic analysis [132–134], coding techniques [135–138], and integration analysis [116] were employed to identify and quantify salient factors of domestic hydrogen acceptance. Overall, this phase of the research resulted in three journal publications (see Appendix D–F), which are summarised in the following sub-sections.

1.4.2.1 Divergent consumer preferences for low-carbon homes

The first output addressed a knowledge gap by examining consumer preferences and visions for low-carbon cooking and heating technologies in the UK (Publication 4:

Appendix D). While previous studies have engaged with the heating side of the transition [53,54,139,140], the cooking dimension remains underexplored [77] beyond the context of the developing world [141–143]. Accordingly, a comparative lens is applied to understand the perceived advantages and disadvantages of gas-based and electric-based technologies for heating and cooking.

A new evidence base is presented to gauge the drivers and barriers to adopting hydrogen homes, which link to technological, financial, and safety perceptions, among other factors. The study is the first to evaluate willingness to adopt hydrogen boilers and hobs, alongside the combined prospect of a hydrogen home, while introducing a multigroup focus by analysing perceptions across different consumer sub-groups. Accordingly, the research advances evidence on market and behavioural aspects of domestic hydrogen acceptance, in addition to attitudinal acceptance, which is a prerequisite dimension of social acceptance [52].

1.4.2.1.1 Gauging public perceptions of blue and green hydrogen futures

The multigroup focus is retained in the subsequent output, which focuses more explicitly on socio-political acceptance (Publication 5: Appendix E). Notably, the first national hydrogen strategy can be traced back to December 2017 with Japan [144], while the United States released their strategy in June 2023 [145], following a draft report in September 2022 [146]. However, beyond primarily the Japanese [147] and Australian contexts [73,148], the research community is yet to engage with public perceptions of national hydrogen strategies [149,150] and developments within the hydrogen economy [151]. In response, this research article provides critical insights on public perceptions of hydrogen production pathways in the UK context (i.e. twin-track approach), and related attitudes towards deploying and scaling up hydrogen homes. The study advances the literature by deriving meta-inferences on public perceptions of domestic hydrogen futures based on qualitative data and statistical findings.

1.4.2.1.2 Price promises, trust deficits and energy justice

In the final stage of the focus groups analysis (Publication 6: Appendix F), a multi-dimensional approach is employed to examine all five dimensions of domestic hydrogen acceptance, according to a specific range of factors: public trust (socio-political acceptance); financial perceptions, consumer engagement with energy

markets, and technology perceptions (market acceptance); perceived community risks, costs, and benefits, and spatial and equity implications (community acceptance); and perceptions of disruptive impacts, and individual risks and energy vulnerabilities (attitudinal and behavioural acceptance). As such, several of the factors identified within the narrative literature review (Appendix B) are operationalised within this stage of the research, leading to extensive findings on domestic hydrogen perceptions in the UK, as contextualised to the current political and socio-economic landscape. Foremost, the analysis presents original findings by identifying specific causal mechanisms behind social resistance to hydrogen homes. Notably, public trust, cost concerns, and equity implications are identified as at-risk acceptance dimensions among citizens facing fuel stress and living in industrial towns.

1.4.3 Research Phase 3: Towards a unified theory of domestic hydrogen acceptance

Following the development of the 5D-DHAF [52], a subsequent research gap was identified in view of the need to further understand adoption potential in the residential context. Furthermore, at this juncture it became apparent that the existing evidence base on domestic hydrogen acceptance – while qualifying for a narrative literature review covering the period 2017–2022 [32] – was too thin for developing subsequent research models. In response, the prior outputs lent themselves towards conducting a more systematic review of both the technology and energy acceptance literature, with an explicit focus on broader hydrogen technologies (e.g. hydrogen fuel cell vehicles and fuelling stations) and domestic energy technologies (e.g. solar rooftop PV and smart meters).

Accordingly, Chapter 2 internalises initial outputs from the PhD project (see Fig. 1-1 and Fig. 1-2) and synthesises a hybrid evidence base through systematic analysis, which sets out to advance theoretical understanding on the topic. An integrative, comparative review is undertaken to bridge a critical research gap on domestic hydrogen acceptance and prospective adoption, culminating in a unified theory which underpins the foundations of this PhD thesis (Chapter 2: Publication 7).

The rationale is consistent with developments in the field of technology acceptance [56,58], as represented within a select number of energy studies [59,60,152]. For example, to (retrospectively) predict the installation of a wood pellet stove among Norwegian households (N = 737), Sopha and Klöckner [153] developed an integrated

approach – the Comprehensive Action Determination Model (CADM) – combining psychological factors, perceived technology attributes, and basic and ecological values. Importantly, the authors clarified the following details to justify the choice of first-generation (1G) statistical analysis (i.e. multivariate regression analysis) [154,155]:

> "The model was not tested as a structural equation model (SEM) with latent variables because most constructs were only measured with one or two indicators which poses a potential threat to an SEM analysis due to under-determination of the latent constructs."

The conceptual framework developed in Chapter 2 internalises seminal research models [156–158] dating back to the 1960s [159], alongside more recent contributions to the technology acceptance literature [49,56,60,160]. Specifically, the unified theory underpinning this thesis draws from Diffusion of Innovation (DoI) theory [159], the Norm Activation Model (NAM) [161], the Theory of Planned Behaviour (TPB) [162],[15] the Technology Acceptance Model (TAM) [156], alongside risk perceptions literature [163,164], trust-based models [165–169], and models integrating affective constructs (i.e. emotions) [58,170–172], in addition to energy acceptance frameworks [40,49,60].

By contrast, established frameworks such as the Sustainable Energy Technology Acceptance (SETA) Model [60] have effectively integrated building blocks from a limited number of theories (i.e. NAM and TPB), which is in the tradition of other seminal contributions to the literature. Notably, Taylor and Todd [173] advanced a Combined TAM-TPB model (C-TAM-TPB), which has also gained traction among scholars [174–176]. Consequently, the early 2000s marked the proliferation of 'decomposed' models of the TPB and extended versions of the TAM, which integrated constructs from DoI such as perceived technology attributes [177–179].

Foremost, this thesis is inspired by the seminal contribution of Venkatesh and colleagues [56], which integrated eight established models of technology acceptance,[16] culminating in the Unified Theory of Acceptance and Use of Technology (UTAUT). Subsequently, the model was extended in UTAUT2 through a focus on consumer acceptance, as opposed to the organisational context, which reflected the

[15] Based on the Theory of Reasoned Action (TRA) which Ajzen developed alongside Fishbein [158].
[16] See Table 2-2.

addition of three new constructs: hedonic motivation, price value,[17] and habit [180]. Crucially, the framework presented in Chapter 2 integrates acceptance constructs associated with both rational decision-making and emotional response, with each pathway influencing acceptance and subsequent adoption prospects. Critically, the third research phase internalises the seminal commentary of Gregor [181]: "Developing theory is what we are meant to do as academic researchers and it sets us apart from practitioners and consultants."

In sum, Chapter 2 provides a starting point to explore the critical success (i.e. positive) and resistance (i.e. negative) factors influencing the dynamics of acceptance and adoption for hydrogen homes; as previously espoused across a range of research contexts such as enterprise resource planning [182], internet banking [183], and e-learning [184]. Unification is achieved in terms of integrating constructs from different branches of theory, which has been shown to increase the predictive power of technology acceptance models [56,61,185].

Accordingly, the unified theory is conceived in line with prior frameworks, which have been adapted and extended by the research community in view of empirical findings.[18] For example, Huijts and colleagues [63,186] refined several constructs and pathways within the SETA in follow-up studies on hydrogen fuel station acceptance. As reflected by Morrison and Morgan [187], knowledge is advanced through the building and subsequent operationalisation of models. In parallel, advancements in research methods and computational power continue to shape the trajectory of scholarship on consumer behaviour and technology acceptance [188–190]. Internalising these observations, this thesis advances two conceptual approaches for distinct purposes, as outlined in the next sub-section.

1.4.4 Research Phase 4: Acceptance and adoption dynamics of hydrogen homes

The final research phase draws on data collected through an online survey (N = 1845), which led a series of research outputs. Two procedures were undertaken in parallel to further derive consumer attitudes and perceptions towards domestic hydrogen

[17] The unified theory of domestic hydrogen acceptance incorporates 'financial perceptions' as an exogenous construct.
[18] Most notably, the TRA evolved into the TPB, while the TAM and UTAUT were followed by subsequent iterations (i.e. TAM2 and TAM3, UTAUT2 etc.).

(Chapter 3: Publication 9), alongside mapping the salient factors of domestic hydrogen acceptance (Chapter 4: Publication 10) and elucidating findings on consumer heterogeneity (Chapter 5: Manuscript 2). Details of the online survey including information provision materials and descriptive results for each question are provided in Appendix H and I, respectively.[19]

1.4.4.1 Typology of domestic hydrogen acceptance

The initial analyses (see Chapter 3 and Appendix G) draw on responses to an open-ended question at the end of the survey, which led to an extensive qualitative evidence base (N =1213). The method mirrors the approach taken by Mohr and Kühl [191] when examining the acceptance of artificial intelligence in German agriculture. In addition to answering Likert-scale survey questions, respondents were invited to answer an open-ended question, thereby adding an exploratory and qualitative dimension to the research [191]. While the highlighted study secured a high response rate to the open-ended question (~82%), it had a relatively small sample size (N = 84) [191], which motivated the use of PLS-SEM [192].[20]

Chapter 3 provides a direct continuum to prior work; building on the acceptance ranking formulated via narrative literature review [32] to establish an empirically-grounded typology of domestic hydrogen acceptance. To derive statistical findings and meta-inferences from qualitative responses to the online survey, the analysis is grounded in an integrated mixed-methods approach [193]. Accordingly, qualitative and quantitative findings are triangulated within the same study [91,116] to support deeper insights and stronger explanatory power [193]. The analysis follows hybrid deductive-inductive coding of qualitative statements [194,195] and data transformation techniques [104] conducted in IBM SPSS Statistics 28.0 [196,197]. The coding procedure enables salient themes and patterns to emerge from within the data [198,199], which can be cross-checked to evaluate validity [136,137].

The proposed typology is developed by grouping empirical data into specific categories according to similarities, and indirectly, by way of shared differences [200]. Through a hierarchical process of categorising ‘core factors’ and ‘sub-factors’ (i.e. primary, secondary, and tertiary factors) [201], the method facilitates the opportunity

[19] Also see the following online resources: https://doi.org/10.17862/cranfield.rd.23585166.v1; https://doi.org/10.17862/cranfield.rd.24517966.v1

[20] PLS-SEM can be employed reliably when a small population restricts the sample size [192].

to quantify the homogeneity within and the heterogeneity between consumer sub-groups [104,200]. In tandem, Chapter 3 leverages insights from a prior contribution (see Publication 3) to categorise consumer attitudes according to an 'acceptance matrix'; consisting of optimistic, hopeful, curious, neutral, cautious, sceptical, and pessimistic positions, as well as two-dimensional combinations thereof (e.g. 'hopeful yet cautious'). Notably, bridging the underlying rationale of the approach, Cristea et al. [202] employed the K-means clustering algorithm to advance a more nuance understanding of public attitudes towards COVID-19 vaccination, thereby expanding the optics of the traditional tripartite typology (i.e. 'pro-vaxxers', 'anti-vaxxers', and 'hesitants').

1.4.4.2 Empirical models of domestic hydrogen acceptance and adoption

In conjunction with mixed-methods analysis performed on the qualitative dataset, PLS-SEM [192,203] and PLS-MGA [204,205] are employed via Smart PLS 4.0 software [206] to derive statistical insights on the acceptance and adoption dynamics of hydrogen homes. Historically, structural equation modelling has proved a popular research method among social scientists [207,208], especially when engaging with consumer acceptance for innovative technologies and services such as smartphones [209] and contactless payments[210], online banking [211–213] and mobile banking [213,214], cryptocurrency adoption [215], e-commerce [179,216,217], and smart home technologies [218–221], among numerous examples.

As highlighted by Acheampong and Cugurullo [222], when multiple factors are involved in the adoption process and several theoretical relationships may exist, as is the case with autonomous vehicles [223,224], proposed conceptual frameworks can be robustly tested using SEM. For example, after proposing the SETA model in 2012, Huijts and colleagues [60] employed SEM to validate its reliability and refine proposed relationships between latent variables [63,186].

Moreover, as described in Chapter 4, PLS-SEM is recommended over covariance based structural equation modelling (CB-SEM) for examining complex relationships when limited theoretical foundations have been established [225–227]. Consequently, PLS-SEM is selected when the goal is to test extensions of the TPB [227–229] or integrated technology acceptance models [230–232]. Fittingly, Haricahandan and colleagues [233–235] recently demonstrated the efficacy of PLS-SEM for studying

consumer behaviour in the domain of the hydrogen economy. Through a focus on consumer attitudes and perceptions towards hydrogen fuel cell vehicles in the Indian context [236], PLS-SEM outputs advanced the research agenda set forth by Huijts and colleagues a decade prior [63,186], which relied on CB-SEM and was therefore limited to testing model fit, as opposed to predictive power [237,238].

The strategic decision to employ PLS-SEM in this thesis is further supported by the study of Rejali et al. [239], which employed the method to explore public perceptions of autonomous vehicles in Iran. The authors aimed to develop a "benchmarking resource" for comparative analysis with countries sharing similar socio-economic and cultural conditions; acknowledging that research on the topic in middle-income countries is scarce in the literature [239].

In sum, through its ability to support hypothesis testing and statistical conclusions via an exploratory, 'causal-predictive' research paradigm [240] – which complements the 'causal-explanatory', retrospective focus of CB-SEM [241] – PLS-SEM "provides the flexibility, robustness, and precision to perform different types of analyses across all disciplines of the social sciences" [242]. Unlike CB-SEM which is predicated on theory confirmation [226,243],[21] PLS-SEM is uniquely suited to examining causal processes in situations where potential end-users are starting to learn about the technology, as evidenced by studies predicting the intention to use Google Glass[22] in the educational environment [244–246].

In Chapters 4 and 5, advanced data visualisation techniques are leveraged by conducting importance-performance map analyses [247,248] for acceptance/adoption constructs and indicators, whereas prior research has overlooked this opportunity [233–236]. In both cases (i.e. for acceptance and adoption intention in Chapter 4, and adoption potential in Chapter 5), the analysis was firstly conducted at the full sample level (N = 1845), while paying close attention to emerging patterns within and between sub-groups for subsequent exploration.

[21] It should be noted that PLS-SEM is also suitable for conducting confirmatory research [240,336].
[22] A mobile wearable platform capable of receiving and sending short-message-service and other messaging formats [337].

1.4.4.2.1 The Domestic Hydrogen Acceptance Model

Chapter 4 models the antecedents of domestic hydrogen acceptance and willingness to adopt hydrogen homes, according to interactions between ten constructs (awareness, knowledge, public trust, production perceptions, safety perceptions, perceived disruptive impacts, perceived costs, perceived community benefits, positive emotions, and negative emotions), which are demarcated according to six specific dimensions: cognitive processes, social trust, environmental attitudes, risk perceptions, cost-benefit appraisal, and affective response. Accordingly, the proposed Domestic Hydrogen Acceptance Model (DHAM) leverages constructs from the unified theory developed in Chapter 2, which are operationalised as exogenous predictors of social acceptance.

Operationalising a baseline model (i.e. where most or all path relationships are posited as direct effects) is an established practice among social scientists when exploring an emerging research area or testing a new conceptual framework. For example, in the context of convenience stores in the United States, Hahn et al. [249] incorporated ten exogenous constructs to examine the relationship between customer satisfaction and customer loyalty.[23] Through meta-analytical structural equation modelling (MASEM), Gimpel et al. [250] analysed the effects of eight technology-specific beliefs, alongside environmental concern, on behavioural intention towards smart energy technologies.[24]

Extending the UTAUT, Al-Saedi et al. [251] examined the behavioural intention to adopt mobile payments in Oman vis-à-vis seven exogenous constructs. Harichandan et al. [234] operationalised five constructs, each with four indicators, for the purpose of investigating motivation to adopt HFCVs in India, whereas Loengbudnark et al. [252] included three constructs (perceived benefits, purchase costs, and safety concern) to examine adoption intention towards battery and hydrogen-based electric vehicles in Australia.[25] Additionally, Sohail and Chen [253] employed five exogenous constructs

[23] Customer satisfaction mediates the relationship between exogenous constructs and customer loyalty, which mirrors the DHAM (i.e. domestic hydrogen acceptance → willingness to adopt domestic hydrogen).
[24] The model also examined the effect of environmental concern (i.e. personality-specific beliefs) on technology specific beliefs.
[25] The model also tested the effects of eight moderators on adoption intention, which included five socio-demographic variables.

to measure public willingness to use water from filtration plants installed by publicly owned organisations in Pakistan.[26]

1.4.4.2.2 Multigroup analysis of domestic hydrogen adoption potential

The subsequent research output (see Chapter 5) models the adoption potential for domestic hydrogen, thereby linking directly to specific elements within the focus groups analyses, such as technology perceptions (see Appendix D), production perceptions (see Appendix E), and financial perceptions (see Appendix F). Building on the DHAM, the study advances the Safety-Technological-Economic-Environmental Perspectives (STEEP) Framework to examine adoption potential, which is measured through a combination of willingness to adopt domestic hydrogen and perceived community benefits. The proposed construct supports the logic of modelling adoption potential according to dimensions of behavioural and community acceptance, as reflected by establishing construct reliability and validity in PLS-SEM.

Critically, the final research output presented in Chapter 5 advances the evidence base by conducting partial least squares multigroup analysis (PLS-MGA) [204,205] using the STEEP Framework. A decision was taken to explore this aspect of consumer acceptance, since descriptive statistics and robustness checks via the measurement invariance of composite models (MICOM) procedure [254,255] indicated greater scope for comparing adoption dynamics.[27] Formally, PLS-MGA tests the null hypothesis that the population parameters (i.e. structural path coefficients) are equal across two sub-groups (i.e. $H_0 : \theta^{(1)} = \theta^{(2)}$) [256].

Since “customers from different market segments can have very different belief structures” [249], social scientists often measure “latent variables (e.g. personality traits, attitudes) for several groups in order to evaluate between-group differences therein” [257]. For example, based on empirical data from a three-year longitudinal study, Jurison [258] investigated the use and user perceptions of different information technologies among four groups in an engineering organisation: engineering managers, project engineers, professionals, and secretaries. Grounded in the perspective of innovation diffusion theory [159], the study employed self-administered

[26] The study also included age, gender, and education as moderators.

[27] Regarding the domestic hydrogen acceptance model tested in Chapter 3, the possibility of PLS-MGA was explored but proved less limited in scope, following results from the MICOM test. Effectively, this meant that less group comparisons and constructs could be reliably analysed, whereas the adoption model could be modelled in its entirety as all statistical requirements were met.

questionnaires and reached following conclusion: "…differentiated implementation strategies focused on specific end user categories are likely to be more successful than a single broadbrush strategy for all users."

Similarly, medical researchers are increasingly "turning to analytic algorithms that allow the use of multiple indicators (variables)," with the goal of better understanding the dynamics of heterogeneity among patients and bypassing one-size-fits-all management strategies [259]. Environmental policy makers also seek information on different segments of the population to support more equitable decision-making [260]. Meanwhile, within a specific sub-group such as nonindustrial private forest owners in the United States, research shows that individuals are unlikely to respond similarly to forest policies intended "to motivate certain investment, managements, and harvest behaviour." Additionally, research conducted in Belgium provides strong evidence that consumer innovativeness and environmental concern significantly influence intention to adopt an electric car [261].

PLS-MGA functions by testing whether statistically significant differences exist between sub-groups, which the researcher identifies *a priori* during the recruitment stage (i.e. BLG, MEG, VEG, FSG) [256,262],[28] as illustrated in Fig. 1-2. When the research design involves no prespecified targeting of sub-groups, the analyst can instead examine whether the sample data is defined by unobserved heterogeneity, which is motivated "to avert validity threats" [263]. SmartPLS 4.0 supports techniques such as finite mixture partial least squares[29] (FIMIX-PLS) [264] and PLS prediction-oriented segmentation (PLS-POS)[30] [263], as respective latent class and distance-based segmentation methods to uncover unobserved heterogeneity in the structural model.[31]

Although latent class modelling affords opportunities to identify consumer segments with similar attitudes and perceptions *a posteriori* [264,265], the method is also prone

[28] This approach is distinct from *a posteriori* approach wherein the research tests for unobserved heterogeneity within the data to identify the plausibility of different segments or 'clusters' [263,338]
[29] Specifically, FIMIX-PLS uncovers heterogeneity by estimating the probability of segment membership for each observation and simultaneously estimating the path coefficient for all segments [264,339].
[30] Specifically, PLS-POS follows a clustering approach with a deterministic assignment of observations to groups and uses a distance measure for the reassignment of observations. As such, the method has no distributional assumptions [263].
[31] Both tests were conducted by the research, which suggested unobserved heterogeneity did not apply to the sample data, as reported in Appendix J.

to limitations in terms of reliably estimating the number of clusters and defining their boundaries (i.e. lack of interpretability regarding the cluster descriptors) [266].[32] For example, Kandiah et al. [267] employed agent-based modelling to show that public opinion dynamics towards water reclamation differ according to membership in opinion clusters (i.e. optimistic, disengaged, alarmed, or conflicted consumers). However, the approach relied on clustering methods with known limitations [268,269], which reflected the additional identification of sub-groups within the main consumer segments (i.e. *adopter* as a subset of *optimistic*, and *resistor* as a subset of *alarmed*) [266].[33] Nevertheless, latent class analysis[34] may prove useful for exploratory research when the goal is "to determine groups that are maximally different by some criterion" [270].

In summary, PLS-MGA should be applied when the analysis is of a confirmatory nature following *a priori* identification of sub-groups, whereas other methods should be applied to groups detected via cluster analysis of similar techniques [271]. Moreover, researchers should approach these methods with caution and due diligence, since using clustering techniques as a subsequent input to run PLS-MGA is conceptually flawed [272]. Such a sequencing would discount the path model relationships specified prior to the analysis, which are the very relationships likely to explain potential group differences [272]. It follows that traditional clustering techniques are subject to conceptual drawbacks,[35] rendering these methods ill-suited for identifying heterogeneity in the relationships between latent variables (i.e. segment-specific differences in structural equation models) [273].

[32] Other methodological challenges may include a high Type I error rate, low statistical power, and limitations in examining higher-order interactions [269].
[33] Specifically, Ward's hierarchical clustering method was used to create four clusters, wherein the random start point for the iterative clustering process biases the cluster membership of the first individual analysed, which motivated the subsequent use of K-means cluster analysis to create a second clustering solution on the cluster averages from the first step. Additionally, multiple imputation was required since 158 respondents could not be sorted into a cluster directly due to missing values.
[34] Latent class analysis is defined in the literature as "a probabilistic modelling algorithm that allows clustering of data and statistical inference" [259,340].
[35] In technical terms, "the identifying assumption of latent class models is local dependence," therefore, "data dependencies that fail to be predicted by the local dependence model are absorbed as additional classes," which "may bias model parameters of interest as well as posterior classifications" [270]. These constraints are also discussed in [341].

1.4.4.2.2.1 Sampling approach to multigroup analysis

While technology acceptance researchers have taken strides to compare two consumer sub-groups or segments [274–276], systematic analyses of heterogeneity regarding energy preferences and behavioural response are yet to be established [277]. Acknowledging recent efforts to address this research gap [278,279], the dynamics of adoption potential are compared between four distinct consumer sub-groups, which include ‘very technology and environmentally engaged’ respondents and ‘moderately technology and environmentally engaged’ respondents, alongside a non-engaged ‘baseline’ group and ‘fuel stressed’ group. Critically, the described approach departs from a more reductive focus, primarily attributed to environmentally engaged and non-engaged consumers (see Chapter 5), by integrating a wider spectrum of archetypes.

Substantial evidence suggests environmental awareness, technology engagement, and attitudes towards adopting new energy innovations influence consumer support for a wide range of low-carbon technologies [280–282] including hydrogen energy technologies [283–286]. For example, Ball [287] showed that between 2009 and 2017, environmental concern and technophilia motivated early adoption of solar PV in Sweden, which is mirrored in the Australian context [288]. Likewise, Plötz et al. [289] found that pro-environmental attitude (β = 0.524) and technological affinity (β = 0.354) have driven early adoption of electric vehicles in Germany, while Wolf and Seebauer reported similar findings among adopters of electric bicycles in Austria [290].

Following Rogers’ DoI framework [159], the importance of adopter categories and attitudes towards technology innovation is well-documented in the energy transitions literature [152,291,292], and presents a focal point of interest for ‘hydrogen futures’ research [68,293–295]. Notably, Rai et al. [296] showed that ‘staying at the frontier of technological innovation’ has promoted solar PV uptake in Northern California, while interest in the technical attributes of solar PV (i.e. technophilia) has proved more prevalent among early adopters in Western Australian [288].

Additionally, consumer innovativeness has been identified as important factor in accepting solar PV in Iran [297] and intention to adopt sustainable household technology in the United States [218]. Moreover, Lozano et al. [73] observed a positive association between Australian respondents who describe themselves as ‘innovators’ or ‘early adopters’ of new technologies and support for hydrogen. Specifically, the

innovator group had an expressed preference for adopting hydrogen appliances for space and hot water heating [73].

Finally, a fuel stressed group is included in response to the growing energy poverty pressures across the UK [298],[36] which have been exacerbated by the international gas crisis [299] and COVID-19 pandemic [300]. Energy poverty is most prevalent and severe among households with the lowest incomes and least efficient homes [301]. As a result, people with disabilities, the elderly, and low-income household may face multiple energy injustices and vulnerabilities [302]. At the macro-level, the hydrogen futures literature acknowledges issues of energy and justice, as reflected by recent studies on green hydrogen projects in the Global South [303], including case studies on Morocco and Namibia [304], among other studies [305–307]. In the Australian context, Sandri et al. [74] engaged more directly with the residential context by examining household energy vulnerability, while research in the UK has focused on hydrogen acceptance among socially deprived communities in the North of England [27,67]. Additionally, Kar et al. [236] operationalised annual income as a moderator to further explore the dynamics of intention to use HFCVs in India.

1.4.4.2.3 Relationship between acceptance and adoption constructs

This thesis engages with an emerging energy technology, which remains at the pre-deployment stage. In terms of the five-stage innovation decision-process conceptualised by Rogers [159], research on domestic hydrogen acceptance corresponds to the 'pre-decision' phase; wherein knowledge and awareness, alongside other factors, shape consumer perceptions ahead of a prospective decision to adopt or reject the technology [308]. During the pre-decision phase, it follows that consumer acceptance contributes towards an individual's adoption potential, which shapes their adoption intention [309], as conveyed in Fig. 1-3. Alternatively, at the aggregate level, social acceptance reflects adoption potential and subsequent intentions across different regions, communities, and households [52].

Data collected during the final research stage followed an iterative process, as outlined in Section 1.3. Specifically, the online survey was deployed in October 2022 following extensive literature review and qualitatively-driven research via online focus groups

[36] Energy poverty levels in the UK increased nearly 50% between October 2021 and October 2022, reaching an estimated 6.7 million households [300].

(February to April 2022). As a result, the constructs operationalised within each structural equation model are extracted from specific question blocks within the online survey. Three question blocks are of primary interest to framing the research approach: (1) perceived community benefits; (2) domestic hydrogen acceptance; (3) and willingness to adopt domestic hydrogen. As reported in Table 1-1, each question block included three questions, whereby perceived community benefits (1) and willingness to adopt domestic hydrogen (3) were subsequently combined to form a new construct, namely, adoption potential (2).

Firstly, separate measurements for economic, social, and environmental benefits are included to form a comprehensive construct for Perceived Community Benefits (PCB). Secondly, domestic hydrogen acceptance evaluates socio-political, community, and individual acceptance in line with the 5D-DHAF [52]. Lastly, adoption intention (i.e. willingness) accounts for attitudes towards each individual hydrogen appliance (i.e. boiler and hob), as well as the combined prospect of a hydrogen home.

As stated, within Chapter 4, the DHAM operationalises a mediating path, namely, Perceived Community Benefits (PCB) → Domestic Hydrogen Acceptance (DHA) → Willingness to Adopt Domestic Hydrogen (WTA), alongside nine additional mediated relationships. Subsequently, the STEEP Framework introduces additional constructs to the DHAM, namely, Technology Perceptions (TP)[37] and Financial Perceptions (FP), while retaining three exogenous constructs from the DHAM (i.e. Perceived Socio-economic Costs, Production Perceptions, and Safety Perceptions). In doing so, the STEEP provides both a continuum and advancement to the prior model, while incorporating additional constructs from the unified theory proposed in Chapter 2. As a result, different aspects of the innovation-decision process are incorporated into the study (see Fig. 1-3), while solidifying a more expansive understanding and deeper narrative regarding the acceptance and adoption dynamics of domestic hydrogen.

Through the causal exploratory lens supported by PLS-SEM, this thesis establishes an innovative approach to help bridge a conceptual and empirical gap towards understanding the acceptance and adoption dynamics of hydrogen homes. Thus, the unified theory developed in Chapter 2 provides the foundations for testing and

[37] Technology Perceptions is modelled as a higher-order construct composed of lower-order constructs which measures perceptions of hydrogen boiler and hydrogen hob performance.

validating a baseline model for domestic hydrogen acceptance in Chapter 4, while the STEEP framework focuses on the critical success and resistance factors influencing adoption potential for hydrogen appliances. Furthermore, Chapter 5 extends the analytical focus to multigroup analysis, following examination of the full sample in the previous step (see Chapter 4 and Appendix K). Linking together the theoretical approach, conceptual frameworks, and quantitative approach realised via PLS-SEM, Chapter 3 supports a more fine-grained understanding of acceptance factors by leveraging insights from extensive qualitative data. Accordingly, each individual chapter contributes a different perspective towards understanding consumer perceptions and attitudes during the formative phase of the domestic hydrogen transition.

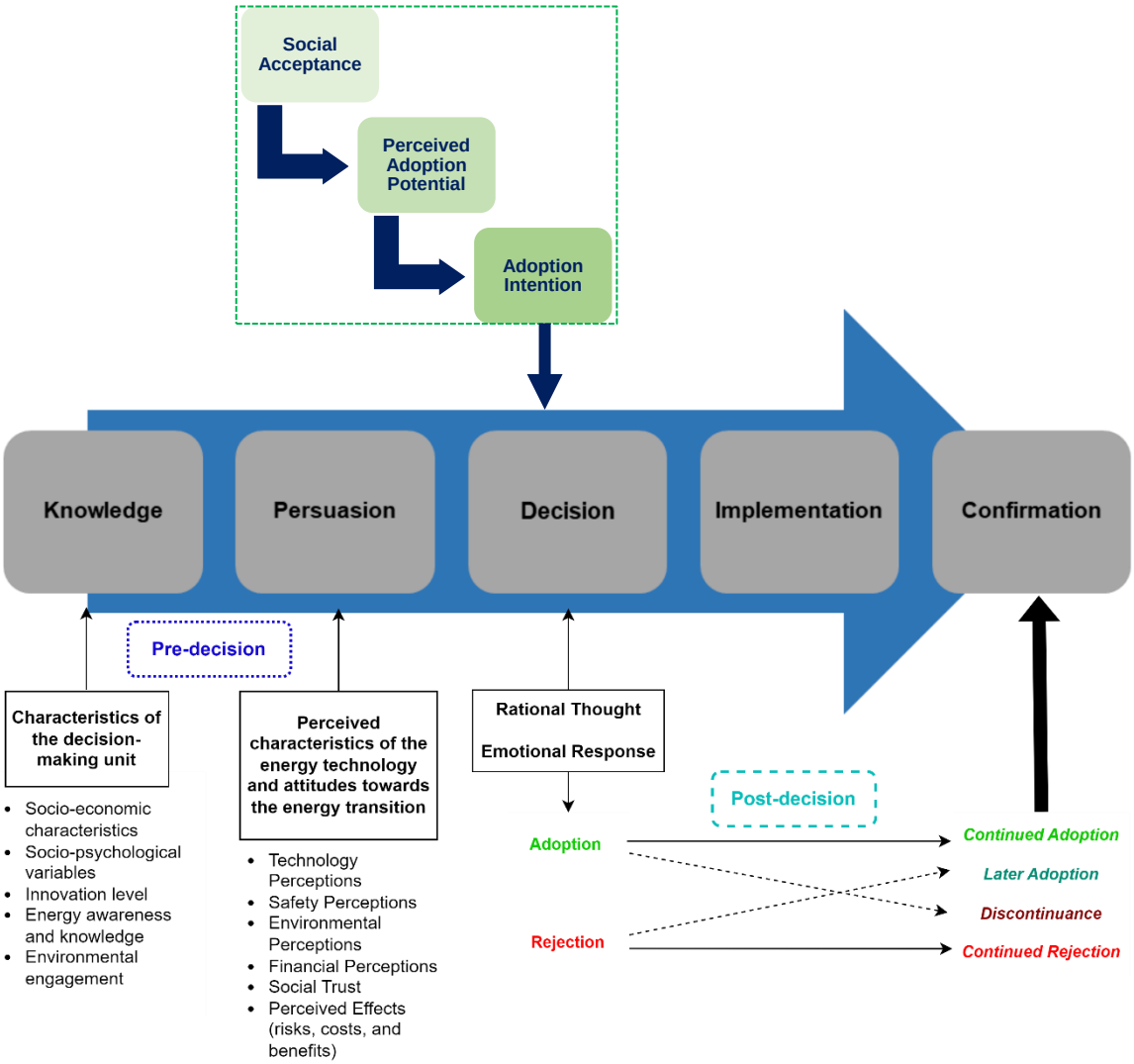

Fig. 1-3. Innovation decision-process for domestic hydrogen acceptance and adoption based on Rogers' Diffusion of Innovation Theory [159].

Table 1-1. Key constructs and respective indicators supporting the DHAM and STEEP Framework.

Dimension	***Social Acceptance***	***Adoption Potential***	***Adoption Intention***
Specified construct	**Domestic Hydrogen Acceptance (DHA)[a]**	**Domestic Hydrogen Adoption Potential (ADPT1)[b]**	**Willingness to Adopt Domestic Hydrogen (WTA)[c]**
Indicator 1	What is your level of support or opposition for hydrogen becoming a critical part of the UK's domestic energy future	What is your level of willingness to switch to a hydrogen boiler before 2030	What is your level of willingness to switch to a hydrogen boiler before 2030
Indicator 2	What is your level of support or opposition for hydrogen replacing natural gas in your local area before 2030	What is your level of willingness to switch to a hydrogen hob before 2030	What is your level of willingness to switch to a hydrogen hob before 2030
Indicator 3	What is your level of support or opposition for switching your home to both hydrogen heating and cooking before 2030	What is your level of willingness to switch to a hydrogen home before 2030[d]	What is your level of willingness to switch to a hydrogen home before 2030[d]
Indicator 4	N/A	Please evaluate your expectations for hydrogen homes delivering economic benefits such as job opportunities and income security in places that switch to hydrogen	N/A
Indicator 5	N/A	Please evaluate your expectations for hydrogen homes delivering social benefits such as reduced level of energy poverty and improved health in places that switch to hydrogen	N/A
Indicator 6	N/A	Please evaluate your expectations for hydrogen homes delivering environmental benefits such as lower carbon emissions and improved air quality in places that switch to hydrogen	N/A

[a] 0 – 10 (Opposed–Supportive)

[b] 0 – 10 (Lowe expectations–High expectations)

[c] 1 – 5 (Not willing at all; Slightly willing; Somewhat willing; Very willing; Extremely willing)

[d] i.e. both hydrogen heating and cooking.

1.5 Research epistemology

Philosophical assumptions underpin the direction of research endeavours and the selection of methods [90]. According to Gregor [181], epistemological questions engage with at least five key aspects: “How is theory constructed? How can scientific knowledge be acquired? How is theory tested? What research methods can be used? And what criteria are applied to judge the soundness and rigour of research methods?”

Regarding the use of mixed-methods research, two epistemological positions are of most relevance, as described by Timans et al. [310]: “a positivist approach that gives rise to quantitative methods and a constructivist approach that is home to qualitative methods.” Additionally, Tashakkori et al. [311] describe ‘three methodological movements’ representing ‘three communities’ of researchers in the social and behavioural sciences, which are outlined in Table 1-2: qualitatively-orientated researchers, quantitatively-orientated researchers, and mixed-methods researchers.

Within the quantitative movement, post-positivism is distinguished from its predecessor, positivism. The former paradigm follows a view that knowledge of the world is developed by testing propositions through deductive reasoning, maintaining that reality can only be approximated [312,313]. By contrast, traditional positivists posit that reality can be understood accurately through empirical observation, characterised by the notion of “self-governing, independent and objective existence of truth,” guided by the ontological assumption that “truth and reality is free and independent of the viewer” [314].

Accordingly, for mixed-methods analyses to be accomplished, the differences between qualitative and quantitative approaches must prove reconcilable within the proposed research paradigm, which requires a certain degree of flexibility towards bridging otherwise divergent epistemological stances, foremost, constructivism and positivism/post-positivism [310]. Ultimately, the pragmatist paradigm [311] entails multiple philosophical assumptions or ‘worldviews’ which shift between research phases [90], as the researcher seeks to leverage the most suitable methods for tackling the questions at hand [315]. Through this approach, methodological pluralism [316] and an integrative research paradigm are upheld [317]. Thus, this thesis reflects the commentary of Majeed [318], which advocates for a pragmatism inquiry to better

comprehend social reality via mixed methods while approaching theory as a continuum.

Table 1-2. The three communities of researchers and methodological movements.

Research community	Research paradigm and methodological approach
Qualitatively-orientated social and behavioural scientists **("QUALs")**	Working primarily within the constructivist paradigm and principally interested in narrative data and corresponding qualitative analysis
Quantitatively-orientated social and behavioural scientists **("QUANTs")**	Working primarily within the postpositivist/positivist paradigm and principally interested in numerical data and corresponding quantitative analysis
Mixed methodologists **("MMs")**	Working primarily within the pragmatist paradigm and interested in both narrative and numeric data and corresponding mixed-methods analysis

Source: Authors' design based on [311].[38]

In this PhD thesis, the empirical analysis is guided by a mixed-methods research paradigm, whereby the different research phases reflect reconciliation between the constructivist and post-positivist schools of thought. The research approach, in its totality, adheres to an exploratory, sequential research design (online focus groups → online survey).

During the second phase, primarily constructivist principles are adopted [90] to develop a richer understanding of domestic hydrogen acceptance by accounting for multiple perspectives vis-à-vis online focus groups. Through interaction with focus group participants, the researcher aims to understand different subjectivities through a critical, rigorous, and reflexive approach [319]. Nevertheless, this research phase preserved a partially quantitative-orientation through data transformation procedures and analysis of poll data to support the qualitatively-driven approach.

To develop a unified theory of domestic hydrogen acceptance, the third research phase follows a three-stage process, which involves two rounds of literature review and the application of thematic coding. Firstly, Chapter 2 undertakes a historical, narrative review of theoretical developments in the technology acceptance literature, which serves to identify the key theories and constructs established in the field. Secondly, a systematic review of hydrogen and energy acceptance studies is carried out, which supports the integrative, comparative component of the analysis. The

[38] Throughout this thesis, all Tables are the author's own design, unless otherwise stated.

analysis leverages from the narrative review by quantifying scholarly engagement with established theories and the prevalence of operationalising different acceptance constructs within empirical analyses. Additionally, the study engages directly with the initial phase of the PhD project by measuring engagement levels across the five dimensions of social acceptance [52]. Both research streams are synthesised to advance conceptual understanding of the acceptance and adoption dynamics of hydrogen homes.

In the fourth and final research phase, two underlying methods are leveraged by drawing on the results of the online survey, in view of the availability of qualitative and quantitative data. One stage involves transforming qualitative data via hybrid deductive-indictive coding to advance an empirically-grounded typology of domestic hydrogen acceptance. The qualitative strand (participant statements) is weaved throughout the analysis (see Chapter 5), while quantitative data from the online survey (i.e. Likert-scale responses) is also used for triangulation and validation purposes, in addition to analysing the transformed dataset. In technical terms, this approach reflects a strictly convergent, mixed-methods design [90,92,128], which captures the pragmatist research paradigm underlying this PhD thesis.

In conjunction, a purely quantitative approach is employed in Chapters 4 and 5. In brief, quantitative analysis adheres to objective and systematic methods which operationalise a given set of variables [320] to measure magnitude and frequency, explore relationships between sub-groups, and test theories [116]. Accordingly, post-positivist principles are adopted to quantify the path coefficients of hydrogen acceptance/adoption constructs and regression weights of their indicators within a structural equation model [321,322]. PLS-SEM applies a deductive approach, since a set of hypotheses are tested following theory development [323,324]. Accordingly, PLS-SEM is predicated on objectivism [325] since a realist ontology is assumed (i.e. the reality of nature is external to the viewer) [314,326]. Thus, the modeller's philosophical position is independent of the data [325] and the focus is on validating the predictive capabilities of the model [327,328].

Specifically, the work reflects a transformative, mixed-methods contribution grounded in a multigroup analysis. Against this background, Section 1.6 closes the introduction

by outlining the structure of the PhD thesis and the links between empirical chapters and objectives.

1.6 Outline of PhD thesis

The background information and motivation for this PhD thesis were provided in **Chapter 1**, in addition to stating the research aims and objectives, and articulating the novelty of the contribution. Following this introduction, **Chapter 2** (Publication 7) develops a unified theory of domestic hydrogen acceptance, which can be adapted and extended in future studies. Next, **Chapter 2** (Publication 9) develops an empirically-grounded typology of domestic hydrogen acceptance through hybrid deductive-inductive coding of over 1000 qualitative responses, and employs a series of statistical tests to explain observed consumer heterogeneity. Subsequently, **Chapter 4** (Publication 10) explores the antecedents of domestic hydrogen acceptance through a multi-dimensional framework. Finally, **Chapter 5** (Manuscript 2) evaluates the antecedents of adoption potential for hydrogen homes and extends the analysis by testing for segment-specific differences between four sub-groups. Following the empirical analysis, **Chapter 6** discusses the general implications of the results presented within the thesis. Finally, **Chapter 7** draws conclusions from the project and provides recommendations for advancing a future research agenda on domestic hydrogen acceptance. Fig. 1-4 provides an overview of the thesis structure and research design.

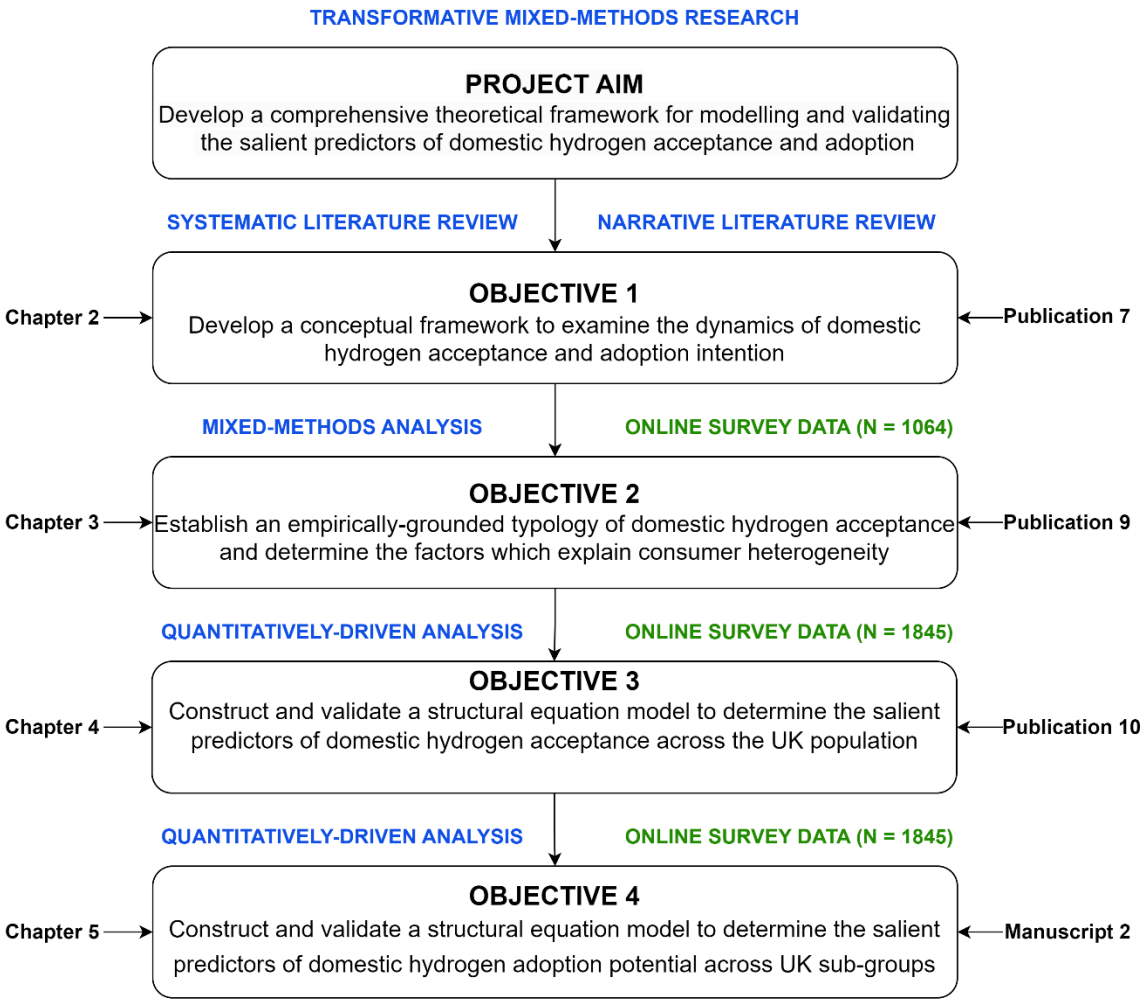

Fig. 1-4. Structure of PhD thesis and links between empirical chapters and objectives.

1.7 Dissemination of PhD thesis

1.7.1 Peer-reviewed journal publications

J.A. Gordon, N. Balta-Ozkan, A. Haq, S.A. Nabavi, Hopes and fears for a sustainable energy future: Enter the hydrogen acceptance matrix, International Journal of Hydrogen Energy 60 (2024). 1170–1191.

J.A. Gordon, N. Balta-Ozkan, A. Haq, S.A. Nabavi, Coupling green hydrogen to community benefits: A pathway to social acceptance?, Energy Research & Social Science. 110 (2024) 103437.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Exploring the contours of consumer heterogeneity: towards an empirically-grounded typology of domestic hydrogen acceptance, Energy Research & Social Science. 108 (2024) 103401.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Towards a Unified Theory of Domestic Hydrogen Acceptance: an integrative, comparative review, International Journal of Hydrogen Energy 56 (2024). 498–524.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Price promises, trust deficits and energy justice: Public perceptions of hydrogen homes, Renewable and Sustainable Energy Reviews. 188 (2023) 113810.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance?. International Journal of Hydrogen Energy. (2023) In Press.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Divergent consumer preferences and visions for cooking and heating technologies in the United Kingdom: Make our homes clean, safe, warm and smart!. Energy Research & Social Science. 104 (2023) 103204.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions, Applied Energy. 336 (2023) 120850.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Beyond the triangle of renewable energy acceptance: the five dimensions of domestic hydrogen acceptance. Applied Energy. 324 (2022) 119715.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition, Renewable and Sustainable Energy Reviews. 164 (2022) 112481.

1.7.2 Manuscripts

J.A. Gordon, N. Balta-Ozkan, A. Haq, S.A. Nabavi, Heterogenous preferences for living in a hydrogen home: A multigroup analysis of UK households, Energy & Environmental Science. (2024) Under review.

J.A. Gordon, N. Balta-Ozkan, A. Haq, S.A. Nabavi, Energy. The dynamics of domestic hydrogen adoption: Safety, technological, economic and environmental perspectives, Int J Hydrogen Energy (2024) Prepared for submission.

1.7.3 Conference presentations

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Forecasting the market dynamics of hydrogen homes: Consumer perspectives on social acceptance and technology adoption, International Conference on Renewable and Sustainable Energy (RenewableEng-2023), 25–27th September 2023, held in Barcelona, Spain/Virtual presentation.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Transitioning to hydrogen homes in a trustless environment: Who should pay for the costs of the transition? British Institute of Energy Economics, Oxford 2023 Research Conference: Energy matters for all: from global actors to active consumers, 20th–21st September 2023, held at Worcester College, Oxford, United Kingdom.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Social barriers to the domestic hydrogen transition: Gauging public preferences for UK policymaking, International Summit on Non-Renewable and Renewable Energy, ISNRE2023, 14–15th August 2023, held at the Renaissance Heathrow Airport Hotel, London, United Kingdom.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Public perceptions of hydrogen risks, costs and benefits: Insights from a multigroup analysis, HyStorPor Final Event – Advanced Hydrogen Research in Scotland, 12th July 2023, held at the Edinburgh Climate Change Institute/Virtual Presentation.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Hydrogen hopes for UK homes? A theoretical approach to breakdown sociotechnical barriers, 13th International Conference on Applied Energy (ICAE2021), 29th November–2nd December 2021, held at the United Nations Conference Centre, Bangkok, Thailand/Virtual Presentation.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Transitioning to hydrogen homes: A critical review of socio-technical barriers to domestic hydrogen acceptance, The 4th International Symposium on Hydrogen Energy and Energy Technologies (HEET 2021), 19–20th November 2021, held at the ANA Crowne Plaza, Osaka, Japan/Virtual Presentation.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Hydrogen homes on the horizon: A critical review of public perceptions of the domestic hydrogen transition, Environmental Research 2021, IOP Publishing, 15–19th November, 2021, Virtual Presentation.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Conceptualising the social acceptance of domestic hydrogen: A critical review of theoretical and empirical evidence, 10th

Annual Energy Policy Conference, From disruption to megatrends in energy, October 14–15th 2021, held at Boise State University/Virtual Presentation.

1.7.4 Poster presentations

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Perspectives on domestic hydrogen futures in the United Kingdom: Insights from online focus groups, *Cranfield Hydrogen and Fuel Cell Showcase, September 20th 2022,* held at Vincent Auditorium, Cranfield University, United Kingdom.

J.A. Gordon, N. Balta-Ozkan, S.A. Nabavi, Examining consumer attitudes towards hydrogen homes: socio-spatial aspects, Energy and Climate Transformations: 3rd International Conference on Energy Research & Social Science, 20th–23rd June 2022, held at the University of Manchester, United Kingdom.

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2 TOWARDS A UNIFIED THEORY OF DOMESTIC HYDROGEN ACCEPTANCE: AN INTEGRATIVE, COMPARATIVE REVIEW

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Statement of contributions

Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Conceptual Framework, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Writing – review & editing, Supervision.

Highlights

- A unified theory of domestic hydrogen acceptance is proposed
- Researchers should integrate multiple acceptance constructs into survey studies
- Comprehensive perceived risks, costs, and benefits predict attitudes toward hydrogen
- Cognitive and emotional processes influence perceptions of hydrogen homes
- Community-level factors should be incorporated into hydrogen acceptance research

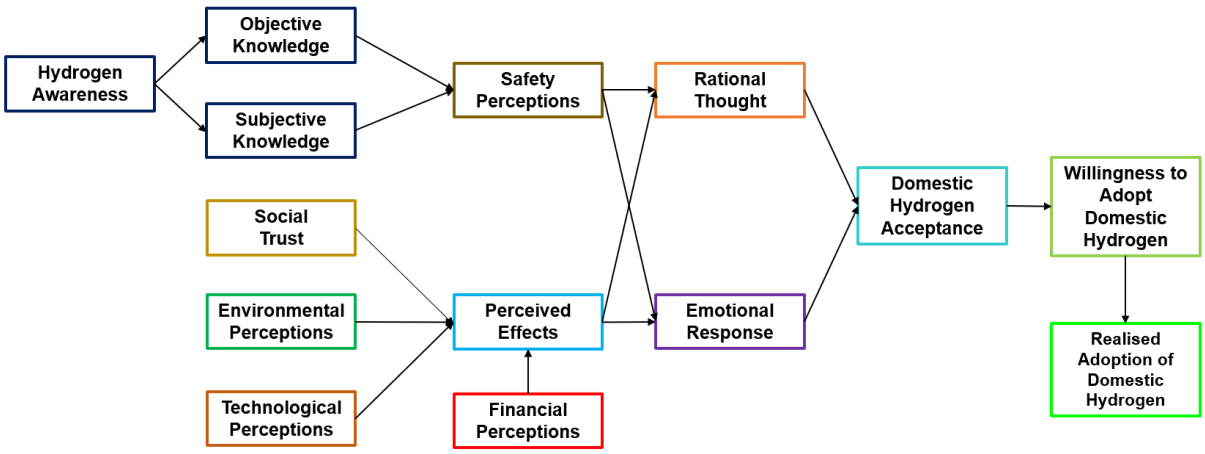
Keywords

Cognitive processes; Domestic energy acceptance; Emotional dimensions; Hydrogen energy acceptance; Social trust; Technological perceptions

Abstract

Hydrogen energy technologies are envisioned to play a critical supporting role in global decarbonisation. While low-carbon hydrogen is primarily targeted for reducing industrial emissions, alongside decarbonising parts of the transport sector, environmental benefits could also be achieved in the residential context. Presently, gas-dependent countries such as Japan and the United Kingdom are assessing the feasibility of deploying hydrogen home appliances, as part of their national energy strategies. However, prospects for the transition will hinge on consumer acceptance, alongside an array of other socio-technical factors. To support potential ambitions for large-scale and sustained technology diffusion, this study advances a unified theory of domestic hydrogen acceptance. Through an integrative, comparative literature review targeting hydrogen and domestic energy studies, the paper establishes a multi-dimensional conceptual framework, which accounts for the cognitive and emotional dimensions of human perceptions. Through this dual interplay, the proposed framework can increase the predictive power of hydrogen acceptance models, while incorporating the potential effects of a range of perceptual antecedents, such as technological, environmental, financial, and safety perceptions. As the hydrogen economy evolves, this study contends that a true litmus test of social acceptance rests with evaluating socio-psychological, cognitive, and emotional dimensions of human perceptions in parallel.

Graphical Abstract



2.1 Introduction

Following several decades of visions and forecasts [1–4], hydrogen is increasingly viewed as a potentially critical energy carrier for supporting a more sustainable global economy [5–8]. While the global potential of hydrogen remains undetermined [9–11] and subject to debate [12,13], the historical record bears witness to the fuel's long, and at times controversial, history [14,15] .

Hydrogen-fuelled energy technologies can be traced back to the early 19th century [16,17], however, present usage remains primarily limited to the industrial sector [18]. As documented by Ajanovic [19], hydrogen fuel cell vehicles (HFCVs) have struggled to penetrate national markets within recent decades, leading to limited global diffusion [20,21]. According to the International Energy Agency (IEA), battery electric vehicles (BEVs) currently outnumber HFCVs more than 350-fold, with market forecasts suggesting this gap could grow exponentially [22]. As a result, some analysts have asserted that HFCVs have already missed their opportunity to compete with alternative technologies for sustainable road transport [23,24].

The lack of market growth for HFCVs presents a cautionary tale for deploying and scaling up other hydrogen energy technologies, such as hydrogen-fuelled appliances for domestic space heating, cooking, and hot water [25–27]. The feasibility of introducing low-carbon 'hydrogen homes' [28] has been explored since at least the early 2000s [29–31]. Notably, Japan emerged as a frontrunner following its early vision for developing a hydrogen-based energy society [31,32], as discussed by Aki et al. [29] in the context of a 'regional hydrogen energy interchange network' among consumers of hydrogen, heat, and electricity in residential areas.

Currently, the buildings sector accounts for approximately 39% of process-related greenhouse gas (GHG) emissions globally and around one-third of final energy demand [33–35]. Prioritising a reduction in residential carbon emissions has been stressed in recent forecasts from the IEA [36–38] and other entities [39,40] including the World Energy Council [41], with growing emphasis in both the European [42] and UK context [43,44]. In response, scholars have discussed the pressing need for transitioning towards net-zero energy buildings, realised through a shift to renewable

or low-carbon energy sources and technologies, efficiency gains, and demand-side management [35,45].

Alongside Japan, other countries [36,38,41] including Australia [46,47], Germany [48,49], the Netherlands [50], and the United Kingdom (UK) [51,52] are exploring the feasibility of deploying technologies to support residential decarbonisation. However, the hydrogen technology innovation system (TIS) remains at the formative phase [53,54], as reflected by demonstration projects [55,56] and local trials for hydrogen homes across parts of the UK [57,58]. Accordingly, the UK government is set to take a policy decision on the role of hydrogen in the residential sector by 2026 [51], which may accelerate the TIS for the wider national hydrogen economy [59].

During the formative phase of the technology cycle [60], new innovations must overcome a wide range of socio-technical barriers [59,61] to bypass risks of non-adoption [62,63] or limited scaling up [64], as currently reflected by the low penetration of heat pumps within the UK market [65]. Consumers may resist technological change due to their belief structures, socio-cultural traditions, or personal behaviours, resulting in a state of resistance and rejection, as opposed to receptivity and acceptance [66–68]. Notably, the global diffusion of sustainable residential energy technologies, such as smart heating and smart meters, remains at a nascent stage [69]. Growth rates have lagged policy and market expectations due to multiple social and behavioural barriers [70–72]. Such barriers have counteracted the potential for low-carbon technology diffusion via a consumer-driven, demand-pull effect in countries such as Germany [69].

Three decades ago, Herbig and Day [73] outlined the need “to ascertain the acceptability and eventual usability of the technology, innovation, or product before the dollars are invested to develop it.” Similarly, Dunphy and Herbig [74] emphasised how “the most successful innovations combine feasible technological bases, entrepreneurial skills, and knowledge of the needs and wants of the customers.” Within the “innovation triumvirate,” Dunphy and Herbig [74] argued that the most important ‘ingredient’ is ‘customer need’:

> Businesses need to understand the reasons behind customer acceptance or rejection in order to become more efficient in their development efforts, and to recognise ways to improve competitiveness and profitability [74].

Despite this long-held argument among technology acceptance and marketing researchers [75–78], and its direct implications for the potential uptake of low-carbon energy appliances [72,79], “the acceptance criteria” of residential consumers remains underexplored in the literature [80] and largely overlooked by policy makers. Notably, several latent dimensions underpinning attitudinal and behavioural energy acceptance are yet to be explored in-depth [81], especially in the context of domestic hydrogen technologies [27,28,58,82].

Although efforts are underway to increase understanding of hydrogen perceptions [28,83], the extant literature provides limited insights as to the validity of identified acceptance constructs [82]. To address this knowledge gap, theory development requires clear identification of the relationships between variables of interest [84], reflecting the notion that hydrogen acceptance studies should be rooted in strong conceptual justification and robust explanation [82]. In response, this integrative, comparative review is grounded in the following rationale: accelerating and sustaining momentum towards realising visions for low-carbon homes will entail developing a better understanding of consumer acceptance [85,86].

To date, researchers are yet to formally codify the dimensions of domestic hydrogen acceptance at the construct level. Given the pronounced knowledge gap, a flexible research approach is needed to advance theoretical understanding; mirroring Huijts’ [87] strategic decision to examine the social acceptance of hydrogen fuelling stations (HFSs) and carbon capture and storage (CCS) in parallel. Following the premise of Ventakesh et al’s. [88] United Theory of Acceptance and the Use of Technology (UTAUT) and subsequent contributions such as the Consumer Acceptance Technology (CAT) model [89], the aim of this study is to develop a unified theory of domestic hydrogen acceptance.

This objective is delivered through a three-stage approach, reflecting a systematic analysis grounded in theoretical, methodological, and empirical rigour [90]. Following this introduction and a description of the methodology, the first stage of the review involves a multi-decadal synthesis of theoretical developments in the field of technology acceptance. This initial stage informs the boundaries for analysis within the subsequent integrative, comparative review focused on hydrogen technologies and domestic energy technologies. In the final stage, previous research strands are

synthesised to provide the critical foundations for establishing a unified theory of domestic hydrogen acceptance. The study concludes by reflecting on research opportunities for advancing the proposed model.

2.2 Material and methods

The applied methodological framework adheres to the recommendations developed by Sovacool et al. [90], advocating for specific “codes of practice” to support “appropriate methods and research design,” wherein theoretical, methodological, and empirical rigour are upheld [91–93] to support transformative research [94,95].

The review components of this study organise, integrate, and assess prior research to identify “relations, contradictions, gaps, and inconsistencies” within the literature [96]. Firstly, the paper undertakes a narrative review of key theoretical developments in the technology acceptance literature over the last six decades, leading to a subsequent systematic literature review (SLR), which is grounded in an integrative, comparative approach.

SLR extensively summarises scholarly literature by identifying, selecting, analysing, and synthesising relevant evidence [97,98]. Grounded in objectivity and reproducibility [90,99], SLR promotes “context-sensitive research” to develop a more comprehensive “knowledge stock” [100]. SLR may include qualitative as well as quantitative evidence [90,100], whereas meta-analysis involves applying statistical techniques (i.e. meta-regression) to synthesise quantitative evidence from several datasets,[39] which are collected via SLR [98,99,101,102].

This analysis implements a novel approach by integrating findings from two distinct energy acceptance literatures, namely, hydrogen energy systems and technologies, and domestic energy technologies. Firstly, results on hydrogen acceptance (N = 33) are presented, highlighting limited engagement with domestic hydrogen technologies for heating and cooking (N = 6). In response, a subsequent review is undertaken to bridge the knowledge gap on domestic hydrogen acceptance, whereby the focus is shifted to a range of domestic energy technologies (N = 42), including solar PV and

[39] Usually via a quantitative index of effect size [99], as recently conducted by Neves et al. [79] in this context.

solar water heaters, smart meters and smart grids, energy-efficient appliances, and low-carbon heating.

Firstly, both datasets are analysed independently to derive insights across four areas: relationships between keywords via bibliometric analysis; scholarly engagement with established acceptance theories; specific interactions with different dimensions of social acceptance (attitudinal, behavioural, community, market, and socio-political acceptance) [58]; and lastly, prevalence of operationalising different acceptance constructs within empirical analyses. Foremost, each acceptance construct appeared across both the hydrogen energy and domestic energy datasets at a suitable frequency to support both individual and comparative analysis.

Subsequently, insights from both research streams are synthesised and leveraged to develop a unified theory of domestic hydrogen acceptance, which can inform the foundations for future models. The comparative assessment introduces a more substantive meta-analytical component to this review, alongside the quantitative assessment of social acceptance via the Five Dimensions of Domestic Hydrogen Acceptance Framework (5D-DHAF) [58]. The approach mirrors previous efforts to unpack linkages between technology adoption predictors [79,103], albeit without the application of robust statistical methods [102,104], which may be incorporated into subsequent analysis.

In summary, the applied research methodology follows a three-stage process consisting of the following outputs: (1) a historical, narrative review of theoretical developments in the technology acceptance literature over the last six decades; (2a) SLR of hydrogen acceptance studies since 2008; (2b) SLR of domestic energy acceptance studies since 2011[40]; (2c) comparative analysis of hydrogen and domestic energy acceptance studies; and finally, (3) developing a unified theory domestic hydrogen acceptance based on the results of previous research strands (see Fig. 2-1).

[40] In addition to one study from 1993 [420] which is included for illustrative purposes and more thorough contextualisation.

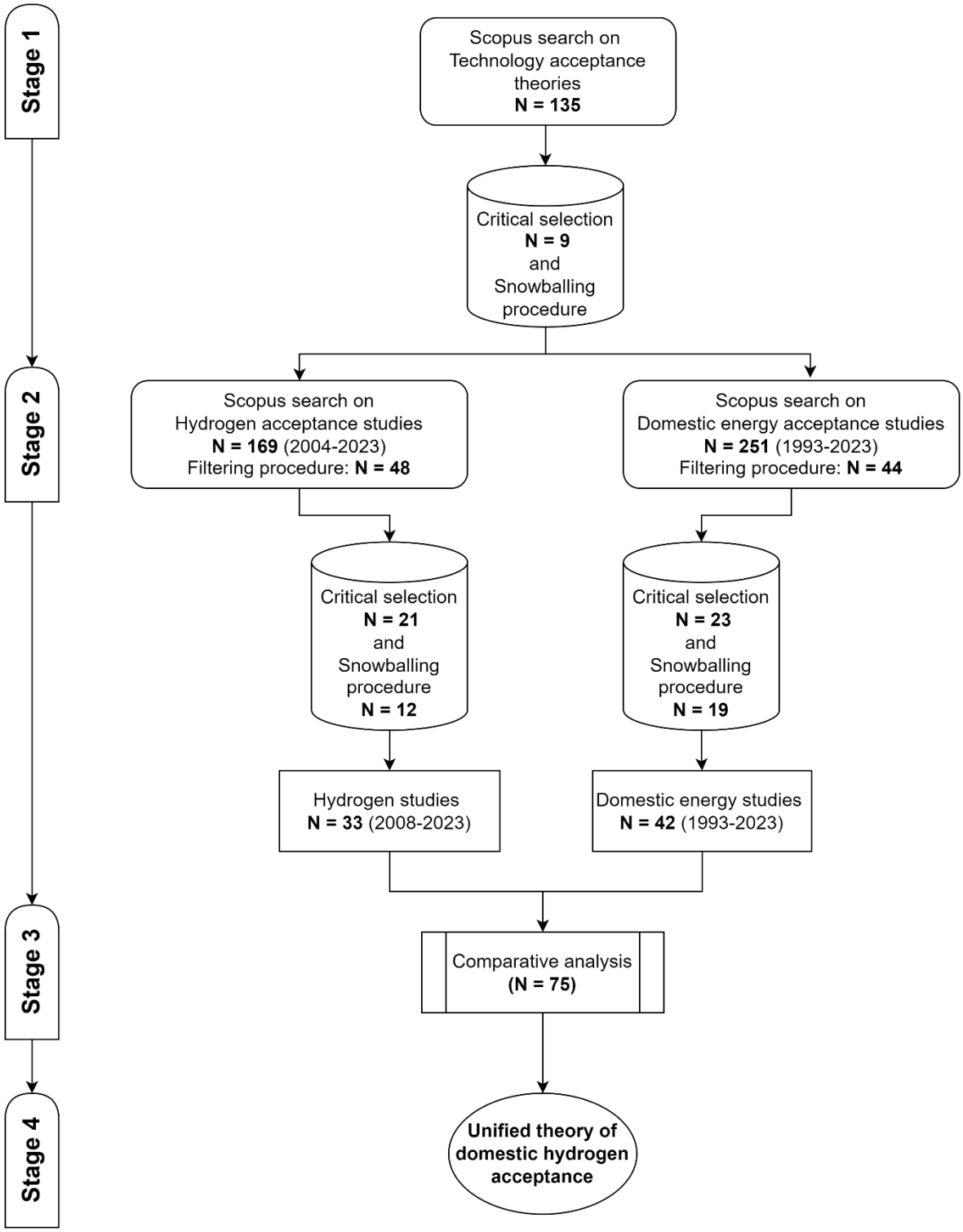


Fig. 2-1. Research stages and selection protocols for reviewed studies.

2.2.1 Materials on technology acceptance

The starting point for this investigation involved a Scopus keyword search for "technology acceptance theories" using article title, abstract, and keywords as the filter. The search returned 135 results when limited to journal articles in English. In

total, nine studies – composed of seminal and more recent contributions – were reviewed in detail to establish a foundational knowledge base on technology acceptance for undertaking a historical, narrative review.

The selected articles supported retrieval of multiple seminal studies through snowballing. The snowballing technique involves identifying materials of interest sourced from reviewed studies within the initial search, which in this case was limited to a small sample (N = 9). Both forward snowballing (i.e. identifying citations of a selected article) and backward snowballing methods (i.e. accessing reference lists) [105,106] were employed to substantiate the sub-sections composing the theoretical review.

Historically, seminal contributions to the acceptance literature have engaged primarily with information systems and technologies [88,107,108]. In addition to distilling the theoretical foundations of this research stream, the narrative review component maps recent contributions [58,109,110] focusing on the social acceptance of low-carbon energy technologies [111]. Consequently, the analysis reflects progression from the organisational context focused on computing technologies, to the consumer context engaging with domestic energy applications. Critically, efforts to advance integrated theories of energy acceptance are also acknowledged, alongside developments in other fields.

While the review builds significantly on prior summaries [112–114] and can therefore stand alone as a historical analysis, the main motivation is to lay the groundwork for systematically evaluating empirical engagement with acceptance constructs across energy studies to develop a unified theory of domestic hydrogen acceptance.

2.2.2 Studies on hydrogen energy technology acceptance

Prior reviews on hydrogen acceptance provide critical insights regarding developments in the literature within the last two decades. The SLR conducted by Emodi et al. [83] retrieved 43 studies for the period 2008–2020 after implementing a stringent search and exclusion criteria to an inclusive keyword search.[41] Considering the final objective of this analysis, it is noteworthy that only five studies focused on the

[41] Emodi et al. [83] applied the following search string: “consumer acceptance” OR “community acceptance” OR “household acceptance” OR “social acceptance” OR “public acceptance” AND “hydrogen”.

domestic energy context, even though grey literature reports were included in the review [83]. Subsequently, Scovell [82] conducted a narrative review of 27 quantitative studies for the period 2005–2021 [82],[42] wherein 15 of the results overlapped with the analysis conducted by Emodi et al. [83].[43] Mirroring prior trends, most studies focused on public perceptions of HFCVs or HFSs [82], which has been further acknowledged in follow-up research [115].

Gordon et al. [28] conducted a narrative review on domestic hydrogen acceptance using a range of databases and keyword searches, which recorded 17 results for the period 2017–2022. However, seven of the retrieved studies provided a partial focus on domestic hydrogen, as opposed to an exclusive focus. Furthermore, among the sample, only six studies were sourced from the academic literature, representing public perceptions in the UK [26,27], Australia [116], and parts of Europe [117–119].

Consequently, existing reviews on hydrogen acceptance reflect an underlying deficiency in available academic studies, especially in the context of residential consumers. Moreover, this synopsis suggests the need for a more comprehensive and up-to-date review to consolidate previous findings. Notably, each of the identified reviews present somewhat disparate search results and research angles.

For the purposes of this analysis, the review of Scovell [82] is the most instructive entry point. Each of the studies analysed by Scovell [82] incorporated constructs from the Sustainable Energy Technology Acceptance (SETA) model [109], leading to a quantitative comparison of scholarly engagement with the following aspects of hydrogen acceptance: perceived effects (perceived risks/safety concerns; perceived benefit/value/usefulness; perceived cost); awareness; knowledge (objective and subjective); experience; social trust; fairness; affect (i.e. emotional response); personal norm; and problem perception/awareness [82].

Acknowledging the research trajectory set by Scovell [82], this study aims to extend the evidence base by reviewing additional studies and applying a new research lens,

[42] Scovell [82] implemented a keyword search with “hydrogen” and several combination terms: acceptance, acceptability, attitude, perception, belief, opinion, intention, behaviour, and behavior.
[43] Four studies reviewed by Scovell [82] predated 2008 [326,344,421–423], while seven additional studies were included for the period 2008–2020 [128,231,273,277,282,424,425], with one sourced from 2021 [293].

whereby selected acceptance constructs are further demarcated according to different dimensions such as psychological, technological, environmental, and financial.

To optimise the retrieval of available hydrogen acceptance studies, the following keyword search was conducted in Scopus, set to article titles, abstracts, and keywords: “hydrogen” AND “public perceptions” OR “public attitudes” OR “social acceptance” OR “consumer acceptance” OR “technology acceptance”. The search returned 169 results for journal articles in English for the period 2004–2023. Following a screening of all titles and abstracts, 48 studies were retained for further analysis. However, only 21 studies qualified for inclusion in the review, whereby all requirements were adequately met for the purposes of analysing theoretical approaches, engagement with social acceptance dimensions, and application of acceptance constructs (see Table L-1 and Table L-2).

Studies were excluded for lacking primary data analysis [28,120,121], or otherwise failing to develop a conceptual framework [122,123] or operationalise an empirical model [124–126]. Furthermore, analyses focused on stakeholder perceptions were discarded [127,128] to preserve a focus on public perceptions. Additionally, cross-country comparative studies [117,118] and longitudinal analyses [129,130][44] were filtered out to help streamline comparative results within the integrative review. Finally, snowballing methods were applied to expand the evidence base, resulting in the retrieval of 12 additional studies, with seven results sourced from 2020–2023 (see Table L-1).

2.2.3 Studies on domestic energy acceptance

The second stage of the SLR involved retrieving international studies on domestic energy acceptance. The following keyword search was undertaken in Scopus, scanning article titles, abstracts, and keywords: domestic energy acceptance OR domestic technology acceptance OR residential energy acceptance, AND theoretical OR theory OR conceptual OR concept OR model.[45] The search returned 437 documents including of 251 journal articles in English, which were eligible for

[44] Achterberg [426] was retained given its ease of interpretation compared to studies conducted in Japan [129,130] covering multiple time periods.

[45] A parallel keyword search was undertaken in Scopus, which returned only 166 journal articles: Social acceptance OR technology acceptance AND domestic energy technologies OR residential energy appliances OR residential energy technologies. After screening both sets of results for valid studies and tracking any duplicates results, the larger search was selected.

screening. Following a review of all titles and abstracts, 44 studies with an explicit focus on energy technology acceptance were included for further assessment. Following this screening stage, 23 studies qualified for inclusion in the final review (see Table L-3 and Table L-4).

Foremost, to ensure the underlying objectives of the literature review could be fulfilled, studies lacking an explicit theoretical framework were discarded (e.g. [131–133]). Additionally, only studies with primary data were included, although meta-analyses such as Schulte et al. [134] and Ganvir and Kalita [135] provided scope for retrieving additional results through snowballing. Furthermore, articles concentrated on technologies operating beyond the household environment such as electric vehicles [136] and battery storage systems [137], or without a consumer-centric focus [138], were also excluded. Similarly, the filtering process removed studies focused on the interaction between different technologies [139] or otherwise restricted to off-grid, rural locations [140].

Drawing on developments in the domain of low-carbon feasibility studies [141], the applied filtering approach follows the logic that reference cases (i.e. domestic energy technologies) should provide a close analogy to the target case (i.e. domestic hydrogen appliances) [141], which is achieved through a shared focus on the residential sector and consumer decision-making. For example, Smith et al. [142] leveraged insights from acceptance studies on genetically modified (GM) foods to elucidate findings in the context of public reactions to water reuse, since both cases involve bodily contact and consumption.[46] In addition to contextual alignment – adhering to the notion of “similar in relevant aspects” [143] – reference and target cases should represent similar social processes and causal mechanisms [141], as reflected in view of convergence between acceptance constructs in this integrative, comparative review (see Section 2.4).

Finally, cross-country comparative analyses were excluded from the review [144–146]; except for the study of Karytsas et al. [147] which presents similar findings across

[46] The efficacy of reference cases has been demonstrated in various contexts such as transportation (i.e. electric vehicles analysed in view of diesel engines) [427] and infrastructure (i.e. CCS storage analysed via oil and gas drilling and pipelines) [428]. Technology analogies have also informed broader understanding of the energy transition [429,430] including the scaling up of green hydrogen supply in the European Union [369].

three countries (Greece, Portugal, and Spain). Through snowballing, an additionally 19 studies were retrieved which satisfied the required criteria (see Table L-4), leading a more extensive sample size (N = 42).

2.3 Theoretical foundations of domestic energy acceptance

This section examines theoretical contributions to the technology and energy acceptance literature since the 1960s, which are subsequently discussed within the context of the domestic hydrogen transition. The first sub-section draws on critical results from a targeted keyword search in Scopus, as reported in the methods. The next three sub-sections follow a broadly chronological order, reflecting historical developments in the technology acceptance literature. The penultimate sub-section forecasts the contribution of this paper by outlining integrated theories of energy acceptance, while the final sub-section summarises the main findings.

2.3.1 Scopus results for technology acceptance theories

Following the Scopus search for “technology acceptance theories” and filtering process (N = 135), nine studies – composed of seminal and more recent contributions – were reviewed in detail. This selection provided sufficient scope to establish a foundational knowledge base on technology acceptance for undertaking a historical, narrative review.

The earliest study, as well as the most citied, was traced to Agarwal’s and Karahanna’s [148] article on ‘cognitive absorption and beliefs about information technology usage’. Critically, the opening paragraph of the paper cites a range of seminal contributions, including “innovation diffusion theory [149,150], the technology acceptance model (TAM; [107,151], the theory of reasoned action (TRA; [152,153], and the theory of planned behaviour (TPB; [154–156])”.

The next most cited study corresponded to Komiak’s and Benbasat’s [157] seminal work, which applied partial least squares structural equation modelling (PLS-SEM) to examine “the effects of perceived personalisation and familiarity on cognitive trust and emotional trust on consumer intention to use a web-based, product-brokering recommendation agent for electronic commerce.” Notably, Benbasat and Moore [158] extended Rogers DoI in the early 1990s, before integrating DoI and the Theory of Reasoned Action (TRA) into subsequent work on technology acceptance [159]. Next, Scopus retrieved the seminal study of Chau and Hu [160], which employed

covariance-based structural equation modelling (CB-SEM) to compare the TAM, TPB, and a decomposed TPB model in the context of telemedicine technology acceptance in Hong Kong.

The remaining Scopus results were selectively considered [161] to extract additional insights. Notably, the seventh most cited study presents a more recent contribution wherein Chao [162] applied an extended version of Ventakesh et al.'s [88] UTAUT to examine the factors predicting students' behavioural intentions toward using mobile learning in Taiwan, which was explored using PLS regression.

Foremost, the eighth most cited study further motivates the current contribution, as reflected by the 2007 publication of Kulviwat et al. [89]: "Toward a unified theory of consumer acceptance technology." The study [89] examined user perceptions of 'high-technology innovation' (Microsoft's Pocket PC operating system) in the organisational setting by merging the TAM and a previously unrelated model, in Mehrabian's and Russell's Pleasure, Arousal, and Dominance paradigm of affect [163], thereby linking traditional acceptance constructs to emotional response.

In addition to the five highly cited studies described, four recent articles were examined (see Table 2-1) before saturation was reached in terms of retrieving a foundational knowledge base from the initial Scopus search. Among the additional studies, David et al. [164] reviewed developments related to the use and application of fourth industrial revolution (4IR) technologies, which provided additional grounds for snowball sampling [165,166] to incorporate findings on controversial and emerging technologies among end-users [167].

Mirroring the research deficit on hydrogen homes, Acheampong and Cugurullo [168] identified "a paucity of theory-driven and behaviourally consistent methodologies to unpack the determinants of user adoption decisions" in the context of autonomous vehicles. In line with the rationale of this study, the researchers leveraged insights from established theories "in social-psychology, social-ecology, and technology and innovation studies" to advance theory-grounded conceptual frameworks [168]. As a result, the selected studies provided inclusive coverage of several established acceptance theories (see Table 2-1) wherein DoI emerged as a starting point for charting historical developments (see Section 2.3.2).

Table 2-1. Summary of results from literature search on technology acceptance.

Authors	Sector and context	Technology focus and research method	Theoretical lens
Juric and Lindenmeier [169]	• Energy • Germany	• Influence of passive and active innovation resistance towards adoption of smart-lighting products • Online survey (N = 653) • PLS-SEM	• Extended Unified Theory of Acceptance and Use of Technology
Meyer-Waarden [170]	• Energy • France, Germany, and China	• Acceptance and resistance factors of adopting artificial intelligence-based smart homes • Online survey (N = 301)[a] • Regression-based moderated mediation analysis using the PROCESS macro	• Extended Unified Theory of Acceptance and Use of Technology
Alshami et al. [171]	• Health • Malaysia	• Factors stimulating or slowing down the adoption of COVID-19 Digital Contact Tracing Apps • Self-administered survey (N = 150) • PLS-SEM	• Unified Theory of Acceptance and Use of Technology
David et al. [164]	• Fourth Industrial revolution (4IR) • Global	• Effects of 4IR technologies on the water, energy, and food nexus for sustainable security • Qualitative methodology and bibliometric analysis of content analysis	• Diffusion of Innovation theory • Technology Acceptance Model
Mohr and Kühl [172]	• Agriculture • Germany	• Behavioural factors influencing the acceptance of artificial intelligence among farmers • Letter or online questionnaire (N = 84) • PLS-SEM	• Integrated Theory of Planned Behaviour and Technology Acceptance Model
Dong et al. [173]	• Agriculture • China	• Factors influencing farmers' intention to adopt ecological agricultural technologies • Self-administered survey (N = 295) • Fuzzy-set qualitative comparative analysis • PLS-SEM	• Integrated Theory of Planned Behaviour and Technology Acceptance Model
Kaur and Rampersad [174]	• Transport • Australia	• Key factors influencing the adoption of autonomous vehicles	• Extended Unified Theory of Acceptance and

		• Embedded quantitative case study comprising an online survey (N = 101) • CB-SEM	Use of Technology
Yuen et al. [175]	• Transport • China	• Factors influencing behavioural intention towards autonomous vehicles • Online survey (N = 274) • CB-SEM	• Combined Diffusion of Innovation theory and Theory of Planned Behaviour model
Rejali et al. [176]	• Transport • Iran	• Factors influencing user acceptance of autonomous vehicles • Online survey (N = 1381) • PLS-SEM	• Theory of Planned Behaviour • Technology Acceptance Model • Unified Theory of Acceptance and Use of Technology
Acheampong and Cugurullo [168]	• Transport • Republic of Ireland	• Behavioural antecedents predicting ownership, sharing, and public transit in the context of autonomous vehicles • Online survey (N = 507) • CB-SEM	• Extended Theory of Planned Behaviour • Extended Technology Acceptance Model • Extended Diffusion of Innovation Theory
Li et al. [177]	• Water • China	• Factors influencing the acceptance of recycled water end-uses and effects on the adoption process • Online survey (N = 564) • PLS-SEM	• Innovation-decision model based on Diffusion of Innovation theory
Lili et al. [178]	• Water • China	• Factors influencing residents' acceptance towards the utilisation of desalinated water • Questionnaire administered to residents (N = 416) • CB-SEM	• Theory of Planned Behaviour
Ahmmadi et al. [179]	• Water • Iran	• Consumer behaviour towards using products irrigated with purified wastewater • Questionnaire distributed to villagers (N = 400) • PLS-SEM	• Extended Theory of Planned Behaviour

[a] France, N = 102; Germany, N = 88; China, N = 111

2.3.2 From diffusion of innovation theory to the Unified Theory of Acceptance and Use of Technology

Developed in the early 1960s, Everett Rogers' Diffusion of Innovation (DoI) Theory marks a seminal moment in the technology acceptance literature [150]. DoI theory posits that "the gradual adoption of an innovation in a market segment or in a society" [180] can be seen as "the process by which an innovation is communicated through certain channels over time among the members of a social system" [150].

The framework provides a powerful foundation for assessing the early stages of technology acceptance, whereby consumers firstly gain exposure to the product or innovation, before attaining a degree of knowledge and awareness to inform their attitudes and adoption decision [181,182]. Rogers' framework has since been applied to a range of contexts [183,184] and features prominently in subsequent theories of technology acceptance, such as the TAM [185] and UTAUT [88,186]. Additionally, the key constructs proposed within the DoI model (see Table 2-2) are generalisable to emerging low-carbon technologies [187], such as hydrogen home appliances [25–27]. Critically, perceived technology attributes such as relative advantage have proved a significant predictor of consumer acceptance in the context of sustainable technology adoption [79].

Following the contribution of Rogers [150], the Theory of Reasoned Action (TRA) [153] and its successor, the Theory of Planned Behaviour (TPB) [188][47] are cornerstones of socio-psychological approaches to human decision-making and behaviour [189]. Both theories adhere to the class of "expectancy-value models," which theorise that consumer behaviour is shaped by beliefs related to how a given product performs and meets specific needs [190]. Consequently, TRA and TPB which have gained prominence among researchers in fields such as social, health, and environmental psychology [191,192]. Notably, social scientists have critiqued and compared both models (TRA and TBP) [193,194], added constructs to test new hypotheses [195,196], and applied these methods to different cases of technology acceptance and environmental behaviours [190,197–200].

[47] TPB added to TRA and has since also been expanded into the Integrated Behavioural Model (IBM) or Integrative Model (IM) [431].

Table 2-2. Overview of seminal theories and models on technology acceptance and human behaviour.

Seminal theory	Author(s) and Year of publication	Theoretical grounding	Constructs or relationships underlying theoretical model
Diffusion of Innovation (DoI) theory	Rogers [150] 1962	Several theories of organisational life from across the social sciences[a]	• Relative advantage • Compatibility • Complexity • Trialability • Observability[b]
Theory of Reasoned Action (TRA)	Fishbein and Ajzen [153] 1975	Social psychology (information integration theory; cognitive dissonance theory)	• Attitude towards behaviour[c] and subjective norms[d] predict behavioural intention, which in turn predicts actual behaviour
Theory of Planned Behaviour (TPB)	Ajzen [188] 1985	Theory of Reasoned Action	• Attitude towards behaviour, subjective norms, and perceived behavioural control (PBC) [e] predict behavioural intention, which in turn predicts actual behaviour
Technology Acceptance Model (TAM)	Davis [185] 1989	Theory of Reasoned Action[f]	• Perceived usefulness (PU) moderates the impact of perceived ease of use (PEOU) and attitudes towards use, and has a direct effect on attitudes towards use and intention to use[g]
Unified Theory of Use and Acceptance of Technology (UTAUT)	Venkatesh et al. [88] 2003	Eight established models of technology acceptance[h]	• Performance expectancy • Effort expectancy • Social influence • Facilitating conditions

[a] Anthropology, early sociology, rural sociology, education, public health and medical sociology, communication, marketing, geography, and general sociology.

[b] Alternatively, some authors use 'expected' (e.g. risks), instead of perceived, as a proxy for potential technology adoption [201].

[c] i.e. Behavioural beliefs (beliefs about the likely consequences of the behaviour).

[d] i.e. Normative beliefs (self-perception of group norms concerning the behaviour).

[e] i.e. 'control beliefs (self-perception of intention and ability to perform the behaviour).

[f] Grounded in Management Information Systems (MIS) attitudes research, MIS laboratory research, Human-computer Interaction (HC) laboratory research.

[g] PU and PEOU can be equated with the relative advantage and compatibility attributes formulated in the DoI model.

[h] DoI, TRA, TPB, TAM, C-TAM-TPB, Social Cognitive Theory (SCT), the Motivational Model (MM), and the Model of PC Utilisation.

Alongside the TRA and TPB, Stern et al.'s [202] Value-Belief-Norm (VBN) theory of environmentalism has been applied to explain consumer attitudes towards both environmental and energy policies [203]. VBN theory is strongly rooted in Schwart's Norm Activation Model (NAM) [204], which presented a framework for examining prosocial behaviours in relation to three basic propositions: an 'obligation', 'activation', and 'defense' proposition.[48] Comparing the TPB and VBN models, Kaiser et al. [205] describe the former theory as "being grounded mainly in self-interest, whereas the VBN is "moral-norms and values-centred" (i.e. normative).[49] Accordingly, scholars have integrated constructs from the NAM, TRA, and TPB to the study of environmental psychology [206–209] and renewable energy acceptance in various national contexts [210–215].

Following the TPB, Davis developed the TAM during the mid-1980s [216]; formalising the model in his seminal contribution to MIS Quarterly Journal [185], which hosts multiple seminal contributions to the field of technology acceptance [88,217,218]. The TAM examines acceptance of the use of information system and information technology innovations in the organisational context [219]. The main antecedents of the TAM are found in the TRA [220]. The TAM was subsequently revised by Venkatesh and Davis in 1996 [221][50] and further refined by the authors in 2000 (i.e. TAM2) [108], leading to the development of TAM3 by Venkatesh and Bala [222] in 2008,[51] as outlined in Fig. 2-2. Foremost, iterations to the TAM were motivated by the need to increase the predictive power of technology acceptance models.

Building on prior contributions [221,223], Venkatesh et al. [88] subsumed multiple constructs from established models of technology acceptance into a single framework (see Table 2-2). Mirroring developments in the tradition of TAM, Venkatesh et al. [218] extended the UTAUT in 2012 to analyse technology acceptance in the consumer

[48] i.e. the intensity of (moral) personal obligation; a cognition of norms and values; and the relevance or appropriateness of feelings of moral obligation [204]

[49] Relatedly, the recently developed Value-Innovation-Congruence model of Emotional responses (VICE model) suggests that positive and negative emotions are reflected by the extent to which an innovation or technology is congruent with people's core values [332,333].

[50] The authors eliminated the attitudinal construct and moderating relationship between PU and PEOU.

[51] One of the notable augmentations of TAM also included the earlier hybrid model developed by Taylor and Todd [196],[51] referred to as the Combined TAM and TPB (C-TAM-TPB). In parallel, Taylor and Todd [194] proposed the Decomposed Theory of Planned Behaviour (DTPB). Notably, Mathieson [432] provides an early comparison of TAM and TPB, prior to the development of the C-TAM-TPB.

context, as opposed to the organisational setting (i.e. UTAUT2).[52] Thereafter, Venkatesh and colleagues [186] proposed a 'multi-level framework of technology acceptance' which synthesised findings from existing UTAUT models and flagged key areas for future study. Other studies have further highlighted ways to link constructs from the UTAUT and DoI theory to better predict technology acceptance [224].

Subsequently, the UTAUT has been widely adopted as a baseline model to examine various applications beyond the IT sector [225], including a wide range of energy technologies [226–230]. Critical to the context of this study, researchers have demonstrated the applicability of UTAUT to examining household acceptance and adoption for smart meters and associated technologies [229,231]. Furthermore, based on a review of the UTAUT literature, Billanes and Enevoldesen [226] identified ten influential factors impacting the acceptance and uptake of a range of smart energy technologies and other emerging applications.[53] Overall, UTAUT-based models have been shown to outperform prior models such as the DoI, TRA and TPB, and TAM [232].

2.3.3 Sustainable Energy Technology Acceptance model

A critical juncture in advancing the understanding of energy technology acceptance coincides the Doctoral thesis of Nicole Huijts [87].[54] Huijts' thesis explored social acceptance and consumer decision-making in the context of two emerging sustainable energy technologies, namely, HFSs and carbon capture and storage (CCS) [87]. This angle helped pave the way for subsequent studies, as literature on energy acceptance gained increasing traction within the last decade [230,233–235].

Huijts and colleagues [109] reviewed evidence from socio-psychological theories and empirical studies from the technology acceptance literature; proposing an integrated framework for examining consumer acceptance of sustainable energy technologies, such as wind farms, CCS, and hydrogen. The SETA framework[55] has subsequently

[52] UTAUT2 incorporated three new constructs (hedonic motivation, price value, and habit), alongside additional moderating variables (age, gender, and experience), with the model explaining 74% and 52% of the variance in consumers' behavioural intention and technology use [218].
[53] Knowledge; awareness; trust; social influence; policy; self-efficacy; compatibility; socio-demographic variables; perceived risk; and perceived enjoyment (i.e. hedonic benefits).
[54] Sustainable Energy Technology Acceptance: a psychological perspective.
[55] The authors refer to their model as the "Comprehensive Technology Acceptance Framework" (CTAF), but across the literature most authors refer to the SETA model, as confirmed within the Scopus search.

been described as “a universal and comprehensive model” of new energy technologies [236].

The SETA model, which has its antecedents in the Norm Activation Model (1977) and TPB [237], includes 16 variables as predictors of ‘intention to accept’ a sustainable energy technology (see Table L-5), which in turn predicts overall acceptance [109]. Notably, the SETA model also internalised the perspective of the Triangle of Social Acceptance (TSA) [110] by distinguishing between different types and scales of energy acceptance.

Numerous energy acceptance studies have adopted or extended the SETA framework to examine public perceptions and consumer attitudes [238–240]. For example, Lozano et al. [239] included several SETA variables when examining hydrogen acceptance in Australia.[56] To quantity the impact of the SETA model [109] on energy acceptance scholarship, a keyword search was performed in Scopus (all fields) for “sustainable energy technology acceptance,” which returned 541 journal articles in English for the period 2012–2022. The results of the search are displayed in Fig. L-1, underscoring the sustained growth of the SETA model across leading energy journals and focal points of research engagement (see Fig. L-2).

2.3.4 The triangle of social acceptance and the five dimensions of domestic hydrogen acceptance

Seminal contributions to the technology acceptance literature demonstrate the efficacy of synthesising traditional DoI theory with socio-psychological models of consumer behaviour, such as the TRA [241] or TPB [242,243], otherwise amalgamated under the UTAUT [225]. Within the renewable energy acceptance literature, researchers have likewise bridged the individual level of decision-making with wider socio-political and socio-economic factors, which can be seen to operate at the macro- or meso-level [58,110,244].

Wüstenhagen et al. [110] proposed a three-dimensional, multi-level framework of energy acceptance, composed of socio-political, market, and community acceptance. Socio-political acceptance operates at the macro- or national level [245], whereas market acceptance “operates at a meso-level between national politics and local

[56] Affect, trust, safety, perceived effects (costs, benefits, and risks), and free-market support.

communities" [246].[57] Community acceptance is shaped by the degree to which local stakeholders are involved in and supportive of new energy plans or projects [110].

Similarly, the technology innovation systems (TIS) framework [247,248] examines technology diffusion as part of an existing socio-technical system [249,250], which may be reshaped by interactions between multiple actors and stakeholders across different scales or levels [251–253]. Relatedly, Wilson and Dowlatabadi [189] describe how the 'socio-technical regime' – constituted by the interrelations between technology, society, and individuals – shapes the diffusion of domestic energy systems.

Reviewing developments in the tradition of renewable energy acceptance, Gordon et al. [58] argued that given its focus on community projects such as onshore wind farms, the TSA is less applicable to energy technology decisions made at the household or micro-level. In turn, the authors proposed the Five Dimensions of Domestic Hydrogen Acceptance Framework (5D-DHAF), which integrates attitudinal and behavioural acceptance as additional dimensions of social acceptance [58]. As described by Demski et al. [254], the 5D-DHAF provides a comprehensive approach for examining "potential socio-technical barriers to domestic hydrogen acceptance."

In a similar vein to traditional technology acceptance models and behavioural theories, the 5D-DHAF posits that dimensions of socio-political, market, community, and attitudinal acceptance must be sufficiently aligned to facilitate behavioural acceptance; realised through the adoption of domestic hydrogen appliances, "established on grounds of cognitive, socio-political, and socio-cultural legitimacy" [58]. Mirroring other low-carbon alternatives [255] such as domestic micro-generation technologies [256], the adoption of hydrogen home appliances will ultimately rest on decisions made at the micro-scale by households and individual consumers [58].

2.3.5 Integrated theories of energy acceptance

Theoretical developments in the literature reflect the emergence and efficacy of combining multiple acceptance theories within analyses. Nevertheless, in 2007, Wilson and Dowlatabadi [189] observed that studies on domestic energy acceptance

[57] Social acceptance can also be interpreted as market acceptance…we can learn from the literature on diffusion of innovation, which explains the adoption of innovative products by consumers through a communication process between individual adopters and their environment [110].

had broadly engaged with four theoretical approaches: (1) neo-classical and behavioural economics; (2) DoI theory and attitude-based decision-making; (3) social and environmental psychology; and (4) sociology [257].

In their weight and meta-analysis of sustainable energy technologies carried out in 2022, Neves et al. [79] noted that most studies had either adapted or extended the TPB or TAM[58] when developing conceptual approaches [79]. While more than a decade apart, both research groups [79,189] advocate for advancing integrated conceptual frameworks to better comprehend consumer perceptions and attitudes towards emerging energy technologies.

It has been shown that consumer preference for adopting domestic energy technologies is driven by a combination of cognitive and psychological factors, wherein rational and emotional parameters of decision-making interact [81]. Fundamentally, a highly "integrated perspective" is needed to examine domestic energy acceptance, which should account for "the interplay between knowledge, psychological and social factors" [258]. Hobman and Ashworth [258] further describe this perspective in terms of examining 'cognitive, knowledge-based factors', 'belief-driven factors', and 'external, socially-derived variables'. Notably, Chadwick et al. [259] responded by constructing a framework of human influences on household adoption and rejection energy technology, rooted in understanding cognitive, social, affective, and behavioural influences, alongside contextual factors.[59]

As the literature has evolved, energy preferences and behaviours have been linked to a range socio-psychological determinants, cultural, and ethical factors [257,260]. Given the complexity of human behaviour and decision-making, a minority of scholars have responded to the call for a more integrated research approach, marking a gradual shift towards developing unified theories of domestic energy acceptance [189,243,261–263]. For example, Bögel et al. [264] integrated approaches from psychology, innovation, and technology transition studies when examining attitudinal acceptance of hydrogen fuel cells in the European context. Furthermore, Elmustapha et al. [262] highlighted "the importance of combining theoretical notions from different

[58] Broadly, models are described in the literature as 'extended TAM' [240,267] when rooted in the tradition of Davis, Venkatesh and colleagues, and 'extended TPB' [211,214] when grounded in the work of Fishbein and Azjen.

[59] The study of Chadwick et al. [259] is additionally noteworthy for combining SLR, content and thematic analysis, and meta-regression techniques to consolidate the proposed framework.

academic traditions," as reflected by results showing more predictive power and better model fit when testing an integrated model against individual components of the model. Beyond the energy sector, the efficacy of a unified theoretical approach has been validated across a range of contexts including transport [168,175], agriculture [172,173], water [265,266], and artificial intelligence [170,267].

While such contributions stand out for drawing on a wide range of theories from across the social sciences to support theoretical pluralism, the need for further exploration has been stressed in recent studies [79,82]. Insightfully, in the context of systemic action research [268], Midgley [269] draws parallels to the underlying premise of linking theory and methods: "…given that different theories inform different methodologies and methods, *methodological* pluralism (drawing upon methods from different paradigms) becomes a useful partner to *theoretical* pluralism."

2.3.6 Summary of technology acceptance theories

This narrative review has traced developments in theories of technology acceptance and consumer behaviour since the early 1960s, thereby linking together historic contributions, as well as more recent and emerging additions to the literature. Fig. 2-2 consolidates the discussion by visualising some of the key links between theories, documented according to their corresponding time-period.

The TAM built on Rogers' DoI theory, as well attitudinal and behavioural insights developed in the TRA and TPB. Taken together, the DoI, TRA, and TPB (grey boxes) can be considered as the building blocks of the technology acceptance literature, which emerged in earnest during the late 1980s and early 1990s; focusing on information systems in the organisational context through a primarily cognitive lens, which carried through into the 2000s [270].

Following the TAM, various iterations were made over the course of the next two decades (blue boxes), which moved towards a greater synthesis of acceptance factors and increased predictive power in models. Among these iterations, the UTAUT [88] is particularly noteworthy for its synthesis of prior concepts, while the UTAUT2 marked a critical shift towards engaging more directly with technology acceptance in the consumer context.

Subsequently, the TAM and UTAUT have been used in a wide range of case studies and contexts to examine "the influence of external variables on the user perspectives

and usage intentions" towards different technologies [271], including consumer behaviour towards different energy technologies [272]. In parallel, the concept of social acceptance was gradually solidified in the literature throughout the 2010s following the contribution of Wüstenhagen et al. [110].

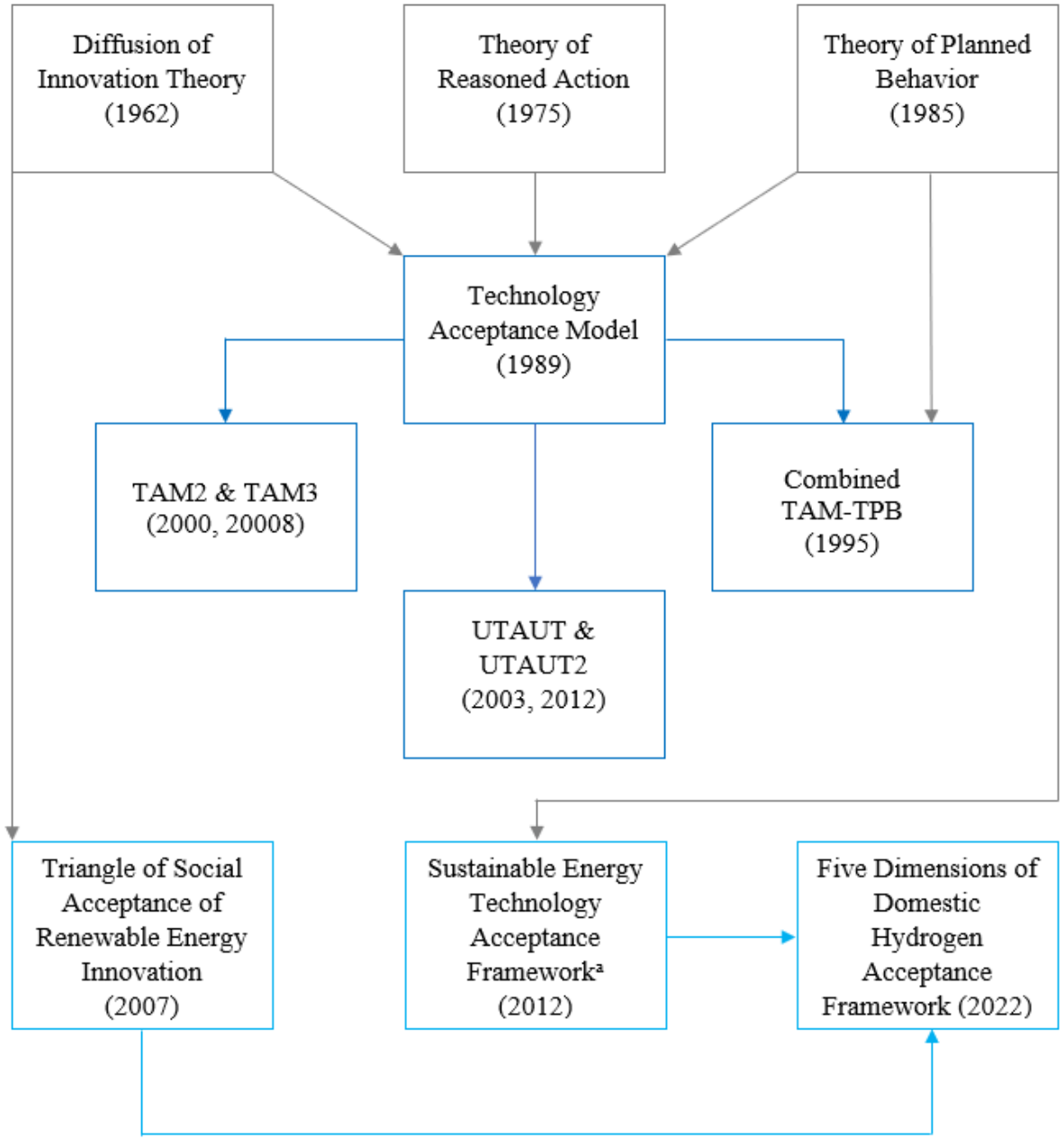


Fig. 2-2. Theoretical developments in technology and energy acceptance, 1962–2022.

[a] In addition to Theory of Planned Behaviour (TPB), the SETA Framework is derived from the Norm Activation Model (NAM) presented in 1977. TAM denotes the Technology Acceptance Model, while UTAUT refers to the Unified Theory of Acceptance and Use of Technology.

Grey boxes = Earliest seminal theories: 1962–1985; Blue boxes = Technology acceptance models: 1989 – 2012; Light blue boxes = Energy acceptance frameworks: 2007 - 2022

Alongside the TSA, the SETA model and 5D-DHAF (green boxes) can be categorised as a turning point in the literature, wherein scholars systematically applied previous insights on acceptance theories to the study of renewable energy innovation projects, sustainable energy technologies, and domestic hydrogen technologies, respectively. This parallel shift in focus, also reflected by the framing of the UTAUT2, has elevated the importance of examining social acceptance and consumer perceptions in the context of sustainable energy transitions [79,259]. Overall, reviewing theoretical developments in the technology and sustainable energy acceptance literatures highlights the scope for developing integrated, conceptual frameworks to increase the predictive capability of models and robustness of quantitative analyses.

2.4 Systematic literature review on energy acceptance

2.4.1 Hydrogen energy technology acceptance

The SLR on hydrogen energy acceptance, as supported by snowball sampling (N = 33), accounted for 20,655 respondents after removal of duplicate datasets (*M* = 617.6; *SD* = 645.5).[60] In total, when accounting for the devolved nations of the United Kingdom (England = 1, Scotland = 2), 12 countries are represented within the sample (Table L-2).

The highest number of studies originate from the Netherlands (N = 7) following several outputs from Huijts and colleagues [273], while emerging research groups in India [274,275] and the United Kingdom [26,276] were equally represented (N = 4), followed by Australia, Japan, and Taiwan (N = 3). Alongside Scotland, China and Germany are represented by two studies each, while Denmark and South Korea had a single study. Regarding research outputs from the Netherlands, it is noteworthy that various studies drew on different theoretical models and explored a range of causal relationships, even when the same datasets were analysed [238,273,277].

Consequently, the geographic distribution of hydrogen acceptance studies is dispersed, albeit highly concentrated around research hubs in Northern Europe, Asia, and Australia. Foremost, European studies present less relative diversity in terms of location and authorship. The observed trends reflect advancements in national hydrogen strategies, with all countries within the dataset (excluding Taiwan) having official policies or roadmaps for developing hydrogen-based energy systems. While it

[60] Huijts et al. (N = 1214) [238,273,277] and Gordon et al. (N = 58) [276,291,292].

is beyond the scope of this integrative, comparative review to analyse policy and research developments in details [278–280], Fig. L-3 highlights the linkages between these two areas.

The links between the retrieved studies were explored in VOSviewer [281], which returned 92 connected keyword items distributed across 12 clusters (N = 112, co-occurrence threshold set to 1). The largest cluster contains 13 items, capturing ‘social acceptance’ and ‘psychological factors’, thereby reflecting the attitudinal acceptance dimension. The second largest cluster (N = 12) includes ‘government policy’ and ‘policy interventions’, and ‘consumer behaviour’, corresponding to the socio-political and behavioural acceptance dimensions. Furthermore, the market and community acceptance dimensions emerge in different clusters, as highlighted by ‘hydrogen economy’ and ‘economics and management’, and ‘place attachment’, ‘energy justice’ and ‘community-led’, respectively. Within one of the smaller clusters (N = 5), different theoretical approaches also prevail, vis-à-vis the TPB, NAM, and TAM. Additionally, structural equation modelling is displayed as ‘SEM’ in the yellow cluster, as a representation of quantitative methods (see Fig. 2-3).

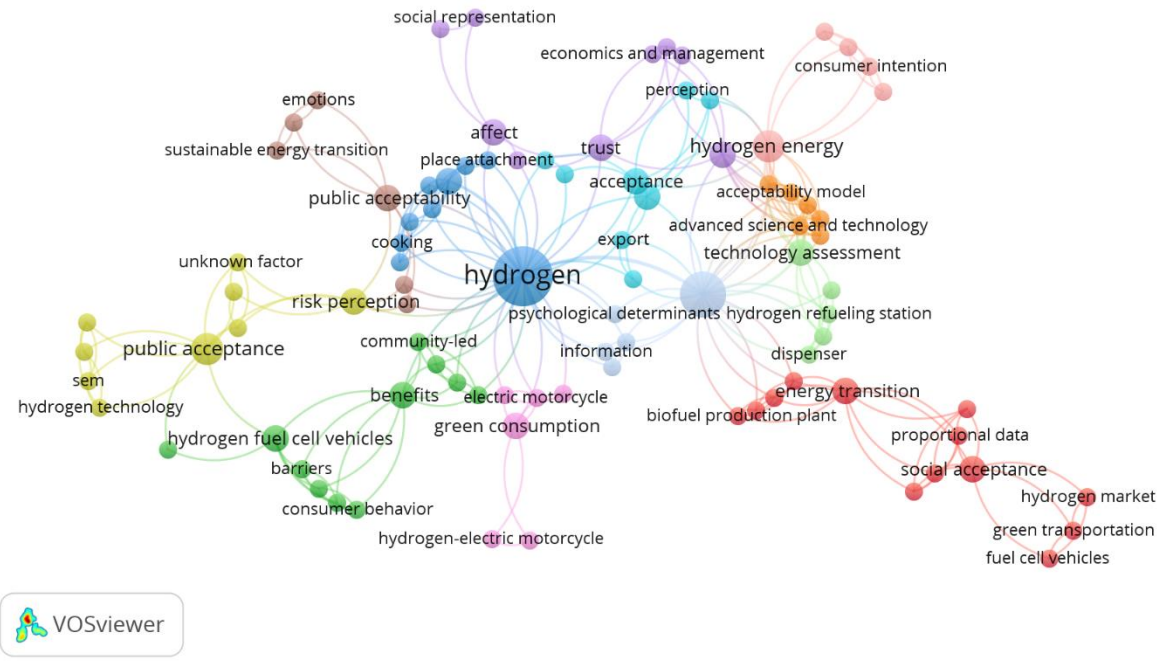


Fig. 2-3. Network visualisation of connected keywords in dataset (N = 33).

2.4.1.1 Theoretical engagement and coverage of acceptance dimensions

From the retrieved journal articles (N = 33), 30 studies applied an explicit theoretical approach, although five studies were classified as miscellaneous due to a more informal use of acceptance constructs [231,282–284], for example, rooted in behavioural economic theory [285], or loss aversion or cognitive dissonance theory [286]. Among the remaining studies (N = 24), seven integrated a two-dimensional approach by drawing on more than one established theory [26,48,275,277,287–289].[61] Consequently, the sample is composed mainly of studies applying a single framework, indicating an underlying deficit in developing integrated acceptance theories within the 'hydrogen futures' literature [2,276].

In total, 16 theories (including adapted and extended frameworks) are represented by the 24 studies, as shown in Fig. 2-4. The largest representation among the sample (N = 19; 54.3%) corresponds to eight theories rooted in a socio-psychological approach (i.e. TRA, TPB, and NAM). Three other categories account for the remainder, wherein studies applied the TSA and 5D-DHAF [26,48,276,290–292], technology acceptance models such at TAM and UTAUT [112,289,293,294], and the SETA [112,238,239,287,295,296] with a relatively similar frequency (N = 7, N = 4, N = 5). Additionally, 21 of the reviewed studies visualised their approach through a theoretical, conceptual, or empirical model, or combination thereof, highlighting the potential scope for developing an integrated hydrogen acceptance model through pooling of results.

Regarding multi-dimensionality, Fig. 2-5 suggests researchers are most likely to engage with four dimensions of social acceptance (N = 15), while there is a growing trend towards engaging with all five dimensions (N = 7), as reflected in recent contributions from researcher groups in Australia [239], India [274,289,297], and the UK [291]. Notably, of the seven studies engaging with all five dimensions, only one study is traced to before 2020 [273]. As a result, one-third of studies (N = 11) are restricted to either three (N = 6) or just two acceptance dimensions (N = 5), highlighting an underlying lack of multi-dimensionality in several earlier contributions to the hydrogen acceptance literature. As a result of recent developments, this trend has

[61] The study of Smith et al. [290] is excluded here on the grounds that the TSA is absorbed by the 5D-DHAF, on which the authors indirectly drew.

been somewhat reversed but still falls short of studying at least four dimensions on average (*M* = 3.7).

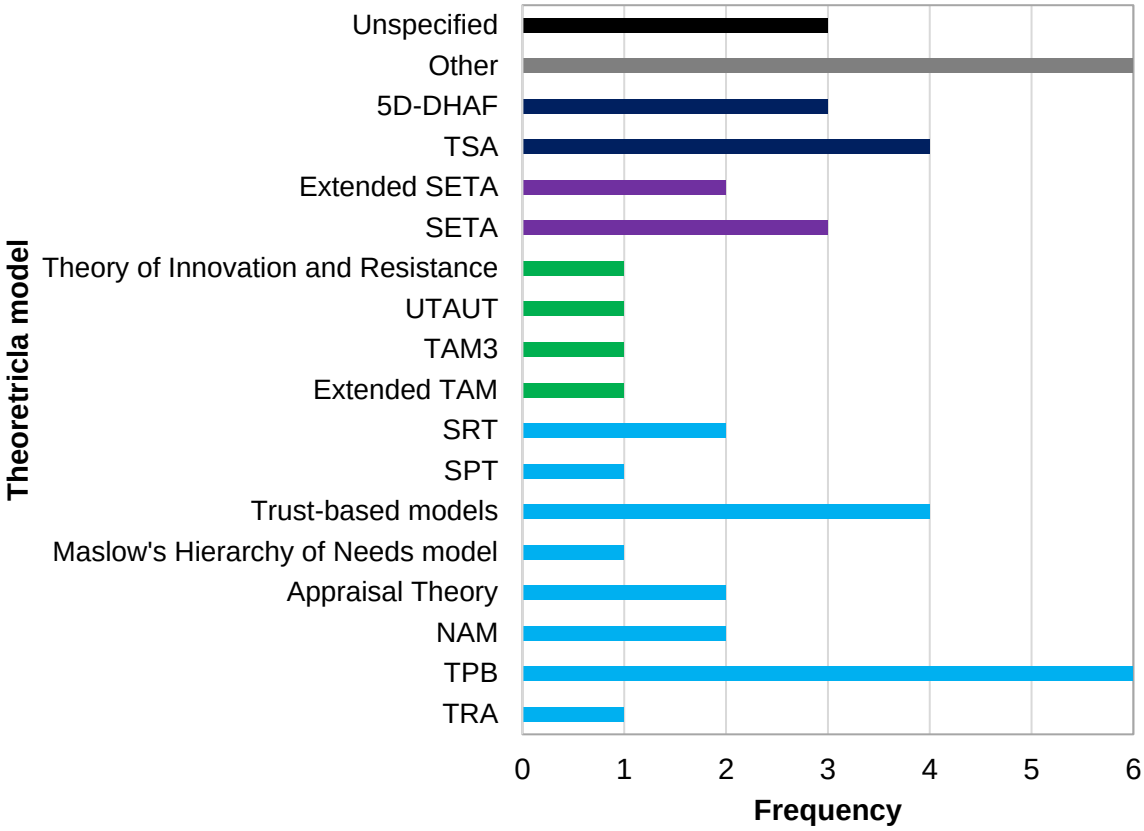


Fig. 2-4. Theoretical approaches across hydrogen energy acceptance studies (N = 33).

NAM = Norm Activation Model; TPB = Theory of Planned Behaviour; TRA = Theory of Reasoned Action; SETA = Sustainable Energy Technology Acceptance; SPT = Social Practice Theory; SRT = Social Representation Theory; TAM = Technology Acceptance Model; TSA = Triangle of Social Acceptance; UTAUT = Unified Theory of Acceptance and Use of Technology; 5D-DHAF = Five Dimensions of Domestic Hydrogen Acceptance.

Light blue = Psychological theories; Green = Technology acceptance models; Purple = Sustainable Energy Technology Acceptance Model; Dark blue = Energy acceptance theories

Fig. 2-6 substantiates the results by quantifying engagement levels with each dimension from across the hydrogen acceptance dataset. It emerges that all social acceptance studies have an explicit attitudinal dimension, given that the focus in on human perceptions. Although a logical finding, this observation has not been reported within studies to help benchmark other acceptance dimensions. Next, most studies entail a focus on socio-political acceptance (N = 29), which likely reflects the broader societal and energy policy implications of developing hydrogen-based energy systems and technologies [59,298].

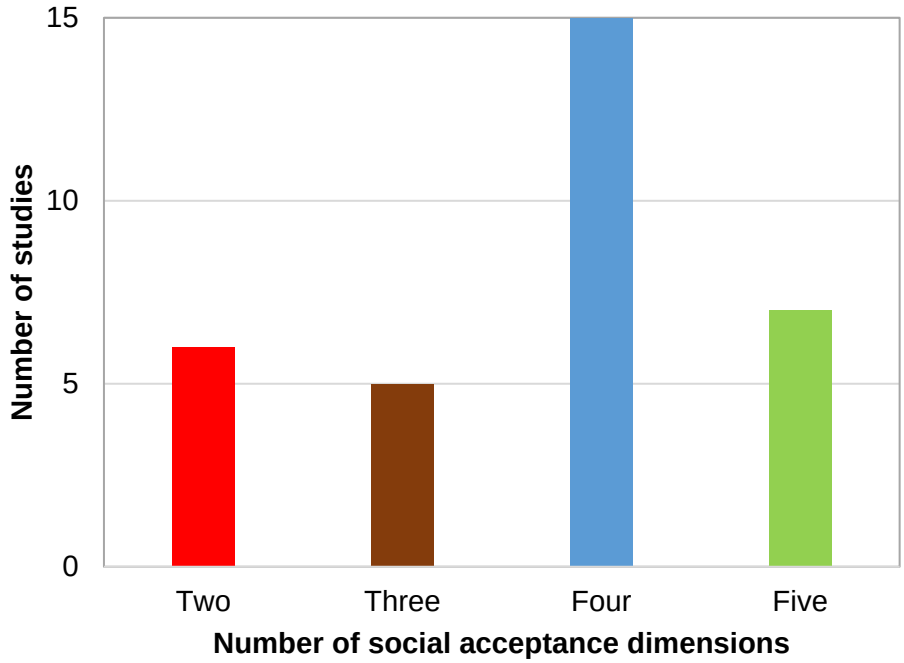


Fig. 2-5. Number of social acceptance dimensions engaged with across sample (N = 33).

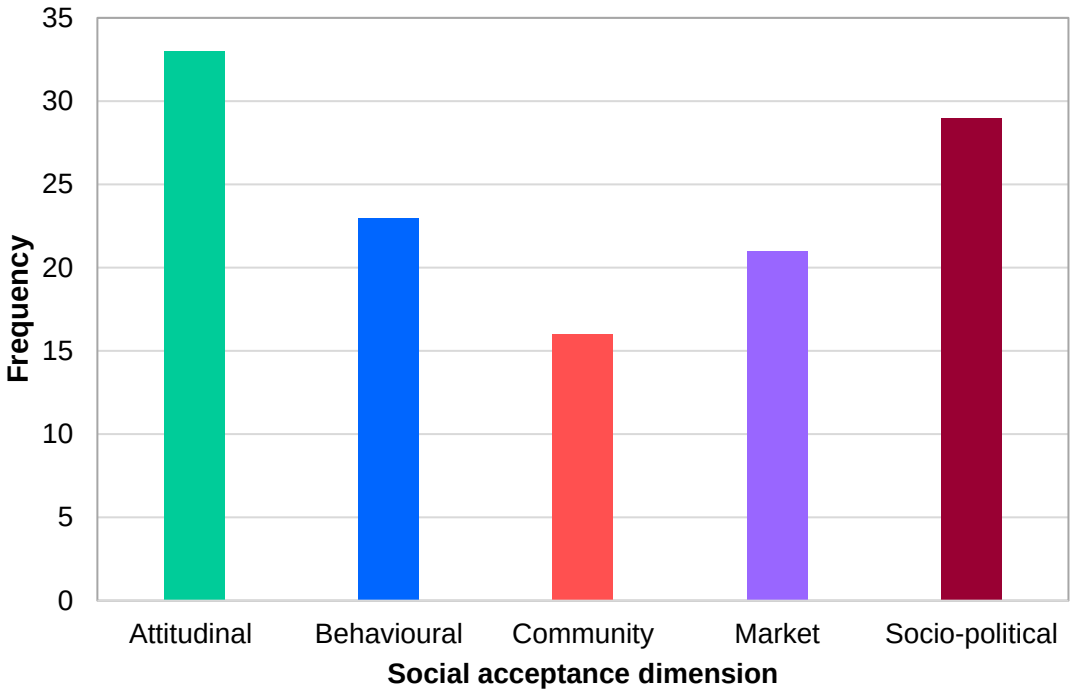


Fig. 2-6. Engagement with social acceptance dimensions (N = 33).

Following the attitudinal and socio-political dimensions, the behavioural component of hydrogen acceptance is moderately represented across the sample (N = 23), as is the market dimension (N = 21). However, it emerges that neither dimension has proved integral to prior acceptance studies, which is most evident in terms of the community

acceptance dimension (N = 17). This finding is significant to the domestic hydrogen transition, as community acceptance is critical to facilitating the development of local trials and changes to infrastructure, while supporting wider approval for a national hydrogen economy (i.e. socio-political acceptance) [58]. For example, factors influencing community acceptance may include public perceptions of equity and fairness linked to spatial dynamics, alongside place attachment and place identity [28].

The partial representation of community acceptance may be somewhat technology-specific, given that 12 studies engaged with hydrogen transport applications (mainly HFCVs), of which only four included a focus on community acceptance. By contrast, six out of the eight studies focusing on HFSs engaged with community acceptance [238,273,277,286,287,296]. Notably, Nicole Huijts is the lead author for all studies on HFSs except one, reflecting a continuum in community acceptance scholarship following the formulation of the SETA model in 2012 [109]. Overall, the data suggests that around 30% of studies, on average, fall short of engaging with at least four dimensions of social acceptance, highlighting the need to move 'beyond the triangle of renewable energy acceptance' [58].

2.4.1.2 Integration of acceptance constructs in hydrogen energy studies

The analysis of hydrogen acceptance studies focuses on 13 constructs representing eight dimensions, as depicted in Fig. 2-7 (see Table L-6: psychological (dark blue); financial perceptions (red); environmental perceptions (green); technological perceptions (orange); perceived effects (light blue); emotional response (purple); safety perceptions (brown); and social trust (gold).

From the original SETA model, the following constructs are represented directly within the analysis presented in Fig. 2-7: perceived risks, perceived costs, perceive benefits, positive emotions, negative emotions (i.e. 'affect') and social trust (i.e. 'trust'). Notably, in a subsequent study on acceptance for HFSs in the Netherlands, Huijts et al. [238] subsumed perceived costs, risks, and benefits under the construct 'perceived effects'. However, a recent critical review of the hydrogen acceptance literature presented by Scovell [82] argued in favour of investigating each variable independently; given that perceived risks and benefits have often proved the strongest predictors of acceptance for several energy technologies.

In view of prior critiques and to delineate clearer boundaries between acceptance constructs, this analysis reconceptualises perceived effects in terms of comprehensive perceived risks, costs, and benefits (see Table 2-3). This adaptation promotes clearer demarcation between environmental, technological, financial, and safety perceptions as antecedents of ***comprehensive perceived effects***. Additionally, the SETA included 'experience' and 'knowledge' as endogenous constructs. In this study, experience is reframed in terms of 'awareness' since consumers are yet to interact with domestic hydrogen appliances. Furthermore, knowledge is separated into 'objective' and 'subjective' knowledge to avoid conflation between these distinct knowledge types, which mirrors the approach implemented by Huijts and van Wee [273] when examining the acceptance of HFSs.

As elaborated within the proposed conceptual framework (see Section 2.5), constructs such as technological, financial, and safety perceptions reflect contributions from other theories and traditions including, DoI, the UTAUT, and risk perceptions literature. This framing reinforces the clear distinction between the SETA, which is rooted in the TPB and NAM, and the analytical lens espoused in this study. Crucially, several constructs composing the SETA (e.g. procedural fairness, distributive fairness, outcome efficacy, problem perception,[62] social norm, perceived behavioural control, attitude, personal norm) are not reflected within this analysis due to a low frequency across both sub-samples (N = 33; N = 45). This discrepancy reflects the contextual differences between the inspiration for the SETA (i.e. TPB and NAM) and the parameters for this study (see Fig. 2-2). Whereas Huijts et al. [109,273,299] focused primarily on issues of community acceptance around infrastructure for HFS, the case of hydrogen homes necessitates a more inclusive focus on aspects of socio-political, market, attitudinal, and behavioural acceptance [28,58].

Table 2-3 forecasts the final contribution of this study by defining each construct to the context of the domestic hydrogen transition. Accordingly, the holistic approach taken within this study internalises Scovell's and Walton's [115] observation to account for salient beliefs about water resources, infrastructure developments, job creation, and technology substitution when considering the hydrogen acceptance context.

[62] However, problem perception is partly reflected by 'environmental perceptions'.

Table 2-3. Predictors of domestic hydrogen energy acceptance.

Acceptance predictor	Definition in the context of hydrogen energy acceptance
Awareness	• Level of familiarity with hydrogen fuel and hydrogen energy technologies, including narratives around the hydrogen energy transition
Objective knowledge	• Factual knowledge of hydrogen fuel regarding its properties, characteristics, applications, and history
Subjective Knowledge	• Self-rated knowledge of hydrogen fuel regarding its properties, characteristics, applications, and history
Social Trust	• Trust in the key actors and stakeholders responsible for supporting a cost-effective, efficient, and fair transition to hydrogen homes
Environmental Perceptions	• Perceived environmental benefits and risks associated with the domestic hydrogen transition and hydrogen homes appliances, as shaped by underlying attitudes towards climate change
Technological Perceptions	• Perceptions regarding the overall relative advantage of hydrogen home appliances compared to existing gas appliances, as shaped by underlying levels of technology engagement and experience
Financial perceptions	• Expectations regarding the potential purchasing, running, and maintenance costs of hydrogen home appliances
Safety Perceptions	• Perceived safety benefits and risks associated with the domestic hydrogen transition and hydrogen homes appliances
Comprehensive Perceived Risks	• Perceptions of potential (non-safety related) risks and disruptive impacts linked to the development and implementation of hydrogen infrastructure and technologies for domestic heating and cooking
Comprehensive Perceived Costs	• Perceptions of potential macro-economic, social, environmental, community, and individual costs linked to the development and implementation of hydrogen infrastructure and technologies for domestic heating and cooking
Comprehensive Perceived Benefits	• Perceptions of potential macro-economic, social, environmental, community, and individual benefits linked to the development and implementation of hydrogen infrastructure and technologies for domestic heating and cooking
Positive Emotions	• Feelings of satisfaction, calmness, confidence, optimism, and other positive emotions towards the domestic hydrogen transition and hydrogen homes appliances
Negative Emotions	• Feelings of discontent, worry, fear, pessimism, and other negative emotions associated with the domestic hydrogen transition and hydrogen homes appliances

Source: Authors' compilation based on [82,87,109,273].

Overall, most studies engage with the dimension of environmental perceptions (N = 28), followed by perceived effects, which is composed of benefits, costs, and risks (*M* = 22.0). Social trust ranked next (N = 19), followed by safety perceptions (N = 18), technological perceptions (N = 16), financial perceptions (N = 14), psychological aspects linked to awareness and knowledge (*M* = 12.7), and finally, positive and negative emotions (*M* = 10.5). Within constructs composed of multiple items, at least

three critical patterns emerge which influence the overall results. Firstly, at the psychological level, objective knowledge (N = 7) is significantly underexamined in comparison to both awareness (N = 16) and subjective knowledge (N = 15), representing the less frequently engaged indicator across all measures.

Secondly, in terms of perceived effects, benefits (N = 24) and risks (N = 25) are examined with a high frequency, ranking behind environmental benefits, whereas perceived costs (N = 17) is relatively underexamined but still ranks ahead of seven other constructs. This result in is partial agreement with Scovell's [82] conclusion that perceived costs has been less explored compared to benefits and risks, but also contradicts the verdict that perceived costs is more underexplored than several other acceptance constructs.

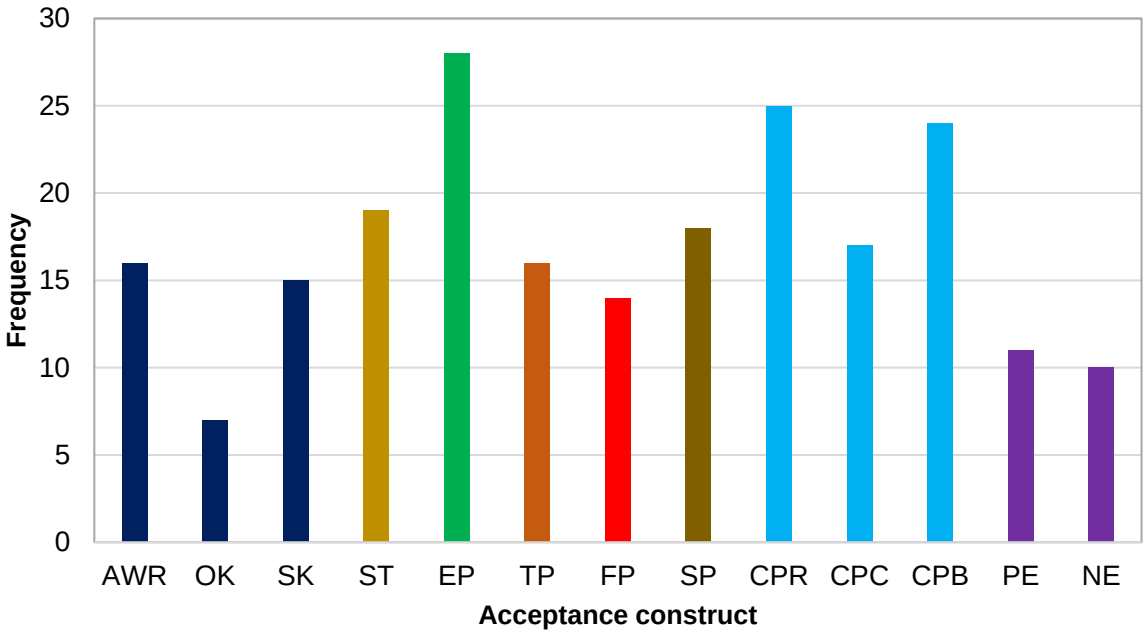


Fig. 2-7. Technology acceptance constructs across hydrogen energy studies (N = 33).

AWR = Awareness; OK = Objective Knowledge; SK = Subjective Knowledge; ST = Social Trust; EP = Environmental Perceptions; TP = Technological Perceptions; FP = Financial Perceptions; SP = Safety Perceptions; CPR = Comprehensive Perceived Risks; CPC = Comprehensive Perceived Costs; CPB = Comprehensive Perceived Benefits; PE = Positive Emotions; NE = Negative Emotions.

Dark blue = Cognitive Processes; Gold = Social Trust; Green = Environmental Perceptions; Orange = Technological Perceptions; Red = Financial Perceptions; Brown = Safety Perceptions; Light blue = Perceived Effects (Risks, Costs, Benefits); Purple = Emotional Response (Positive Emotions, Negative Emotions).

Lastly, the analysis suggests that researchers tend to include both positive and negative emotions when examining the affective dimension of hydrogen acceptance, which is recommended to capture the paradoxical nature of technology perceptions [161]. While this dual focus may be anticipated, it is important to clarify whether either side of the emotional spectrum has received more focus in studies to date. Such a skewing, if detected across a larger sample size, would infer more interaction with perceived benefits in the case of a positive focus, whereas perceived risks and costs would feature under a negative lens. Accounting for a spectrum of emotional responses [300] is needed to reflect the paradoxical nature of technology adoption [161]; characterised by potential friction between different emotional states [301,302] and 'blends of emotions' [63] in view of perceived of risks, costs, and benefits.

2.4.2 Domestic energy technology acceptance

The systematic literature review on domestic energy acceptance, as supported by snowball sampling (N = 42), accounted for 25,854 respondents (*M* = 615.6; *SD* = 645.5) from across 27 countries, with 70% of the representation originating from Asia and Europe.[63] To explore the patterns within this dataset, the VOSviewer bibliometric software tool [281] was employed for network visualisation purposes.

Mapping the relationships between 95 connected keywords (N = 163) led to the formation of ten clusters, revolving around keywords such as social acceptance, technology acceptance and TAM, diffusion of microgeneration technologies, perceived benefits and psychological benefits, and SEM (see Fig. 2-8). Different dimensions of acceptance were also captured within the visualisation, including the socio-political dimension (e.g. business ethics and sustainability), market dimension (e.g. willingness-to-pay, affordability, and purchase intention), attitudinal dimension (product knowledge and knowledge transmission), and behavioural dimension (e.g. intention-behaviour gap). However, clusters representing the community acceptance dimensions were less visible.

[63] Asia = 10; Europe = 9; Middle East = 3; North America = 2; Africa = 1; Central America = 1; Oceania = 1. Less critical focus is placed on examining the domestic energy technology dataset as the primary focus of this study is on hydrogen acceptance.

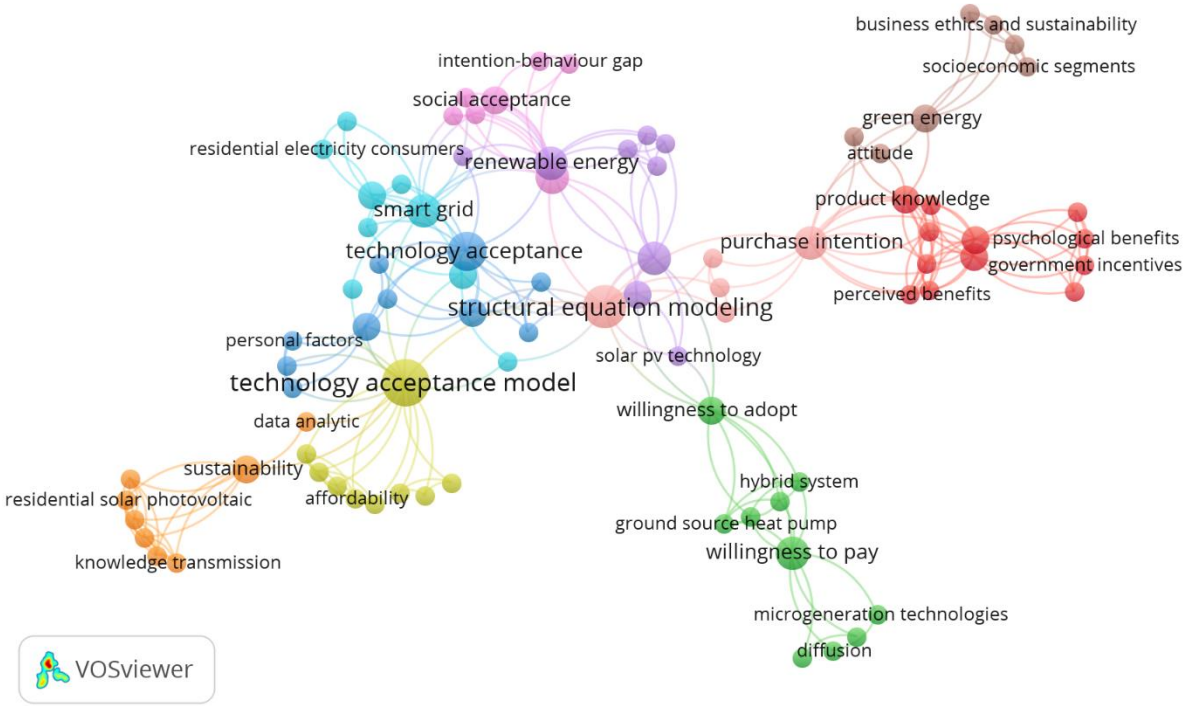


Fig. 2-8. Network visualisation of connected keywords in dataset (N = 42).

2.4.2.1 Theoretical engagement and coverage of acceptance dimensions

From the retrieved journal articles (N = 42), 12 studies integrated at least two theoretical frameworks into their conceptual approach [81,147,230,303–311], whereas 30 employed a single framework. Among the 12 studies adopting a hybrid approach, 9 focused on rooftop solar PV, suggesting a stronger propensity for integration among solar acceptance scholars. Notably, three studies [81,230,305] within this group[64] also incorporated more than two theoretical frameworks, thereby aligning to the underlying premise of this contribution.

The most frequently applied theoretical approach (N = 20) stems from the socio-psychological school of thought rooted in the TRA and TPB, with extended versions of the TPB dominating this group (N = 12). Rogers' DoI theory also features prominently (N = 12), with most scholars extending the framework in their analyses (N = 10). Notably, extended versions of the SETA (N = 12) are represented with the same frequency as extended TBP and DoI approaches, confirming the critical uptake of the framework within the last decade (see Fig. 2-9). Next, various applications of the TAM and its derivatives such the UTAUT account for most of the remaining studies (N = 11)

[64] Two studies on rooftop solar PV and one on domestic microgeneration technologies.

while a selection of frameworks including the TSA are represented by a single study (N = 5).[65] Consequently, most studies within the dataset have strived to adapt or extend seminal frameworks when examining domestic energy acceptance, thereby advancing theoretical engagement to an extent.

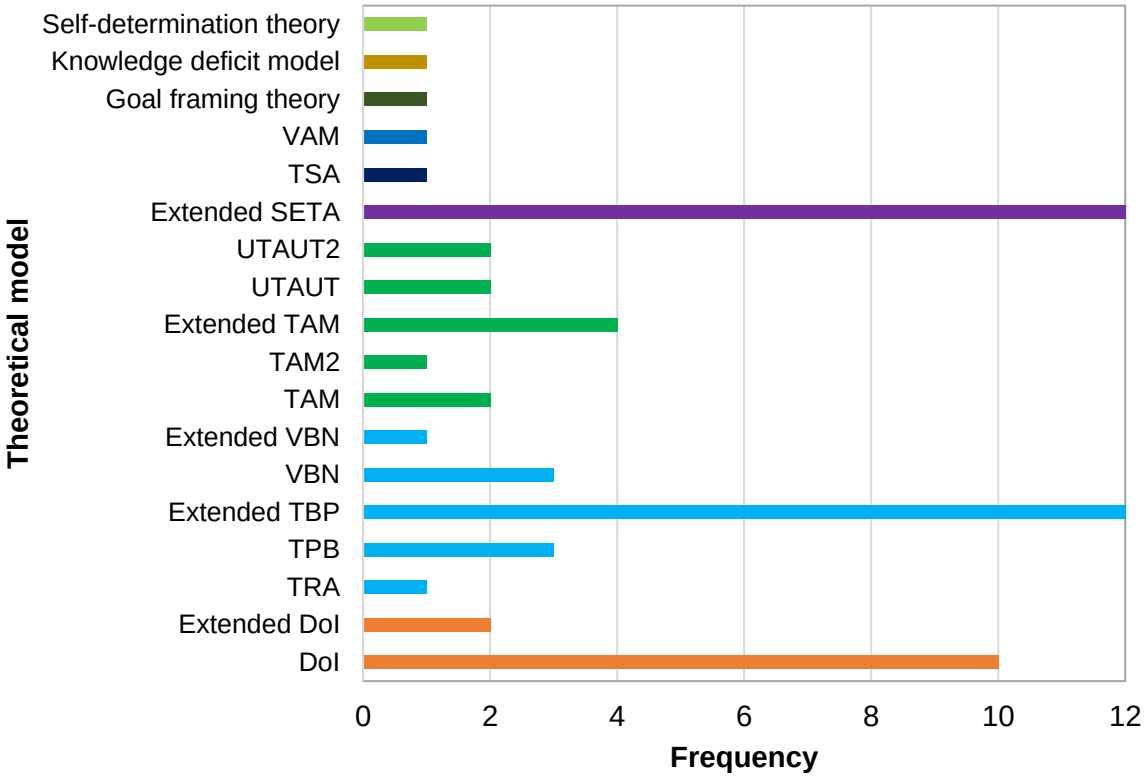


Fig. 2-9. Theoretical approaches across domestic energy acceptance studies (N = 42).

DoI = Diffusion of Innovation Theory; NAM = Norm Activation Model; TPB = Theory of Planned Behaviour; TRA = Theory of Reasoned Action; SETA = Sustainable Energy Technology Acceptance; SPT = Social Practice Theory; SRT = Social Representation Theory; TAM = Technology Acceptance Model; TSA = Triangle of Social Acceptance; UTAUT = Unified Theory of Acceptance and Use of Technology; VAM = Value-based Adoption Model; VBN = Value-Belief-Norm; 5D-DHAF = Five Dimensions of Domestic Hydrogen Acceptance.

Orange = Diffusion of Innovation Theory; Light blue = Psychological theories; Green = Technology acceptance models; Single colours = Theories representing by a single study.

Evidence suggests a growing trend regarding the integration of theoretical or conceptual models, as visualised within journal papers. Across the dataset, nearly

[65] Within this group, we include the study of Xu et al. [433], which drew on the Value-based Adoption Model (VAM) proposed by Kim et al. [434]. The VAM examines the effects of perceived benefits and sacrifices on perceived value, which predicts adoption intention.

80% of studies (N = 33) supported their conceptual approach or proposed hypotheses with a corresponding figure, with all studies after 2020 (N = 18) reflecting this decision. Among the studies lacking a visualisation, the first four studies in the dataset (1993–2013) accounted for this group, alongside five studies in the intervening years (2014–2019). Based on these trends, it may be inferred that the incorporation of a supporting visual has become a research norm for studies grounded in theory.

In terms of multi-dimensionality, Fig. 2-10 shows that researchers tend to engage with four dimensions of social acceptance (N = 24), although a minority of studies focused on just two dimensions (N = 4). Meanwhile, the remaining studies were split equally between three and five dimensions (N = 7). The results suggest a multi-dimensional approach to the study of domestic energy acceptance is somewhat established among the research community (*M* = 3.8). Nevertheless, few scholars have explicitly engaged with all social acceptance aspects proposed with the 5D-DHAF.

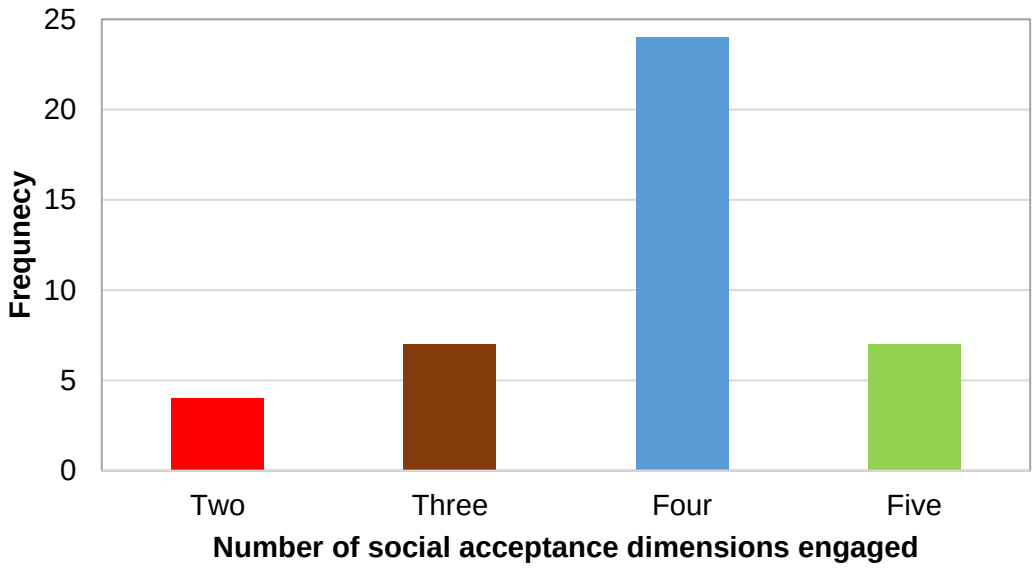


Fig. 2-10. Number of social acceptance dimensions engaged with across sample (N = 42).

Fig. 2-11 provides an explanation for these trends by quantifying engagement levels with each dimension from across the dataset. In contrast to the attitudinal dimension, the behavioural component of social acceptance is not a prerequisite for analysis (N = 39), while the market acceptance dimension is slightly less represented (N = 35), as are socio-political aspects (N = 33). Taken together, these findings imply that around 15% of studies, on average, overlook either behavioural, financial, or broader societal

implications of technology change. However, community acceptance (N = 12) is the most overlooked dimension within the literature on domestic energy technologies.

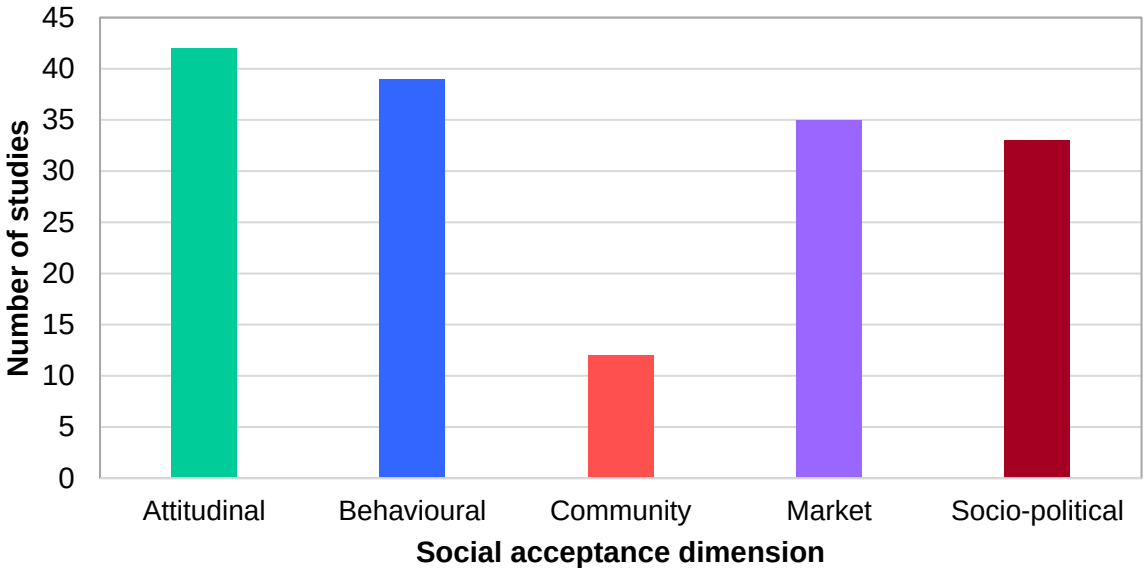


Fig. 2-11. Engagement with social acceptance dimensions (N = 42).

Mirroring the logic that attitudinal acceptance is a prerequisite dimension, while behavioural acceptance is typically incorporated into hypotheses, with market and socio-political aspects relatively well-represented, it follows that community-level perceptions may prove less pertinent to domestic energy adoption. However, close to 30% of studies within the dataset challenge this notion by incorporating a direct focus on how adopting a given household technology may interact with community acceptance.

Considering the perceptions of both adopters and non-adopters, focal points may range from impacts to the local area and property, to behavioural feedback loops between neighbours and residents [312], which could imply different social pressures and market dynamics (i.e. changes to land and property value). Accordingly, acceptance at the community level interacts strongly with other areas, reinforcing the utility of incorporating factors from across all five acceptance dimensions.

2.4.2.2 Integration of acceptance constructs in domestic energy studies

The analysis of acceptance constructs across the sample (see Table L-7) shows most engagement with the environmental dimension (N = 35), followed closely by technological perceptions (N = 33), and financial perceptions (N = 31). Thereafter, perceived effects is the most represented dimension (*M* = 24), while the remaining

areas are significantly underexplored. Foremost, safety perceptions are rarely accounted for in domestic energy acceptance studies (N = 4), while the emotional dimension is commonly overlooked (*M* = 7.5). Finally, psychological constructs (*M* = 13.7) and social trust (N = 13) have a near equal weighting across the sample, which fall towards the lower end of engagement.

The findings of this review both align with and contradict results reported by Marikyan et al. [313] covering the period 2002 to 2017 (N = 143),[66] whereby 101 articles were retrieved through snowballing. The authors noted that environmental and financial factors (i.e. benefits) were less frequently discussed across the sample, while least attention was given to socio-cognitive and emotional factors [313]. By contrast, Fig. 2-12 suggests environmental and financial perceptions are well represented, whereas in agreement with [313], knowledge, social trust, and emotional response are poorly represented. Additionally, Fig. 2-12 supports the strong representation of technological perceptions and perceived benefits, as also reported for the period 2002-–2017 [313].

Given the different time periods and research angles, it is somewhat anticipated that trends may have evolved within the last five years; or reflect different approaches wherein theoretical foundations are applied more strictly. Most critically, following the premise of this study, Marikyan and colleagues [313] called for a multi-dimensional approach, suggesting “future research could examine the emotional, psychological, symbolic, functional and financial antecedents that trigger users to accept or reject smart home products.”

Similarly, Ozaki [314] argues that consumer acceptance of ‘green’ electricity hinges on a combination of external factors such as costs and performance, as well as socio-psychological factors such as identity, values, beliefs, and cultural disposition [314]. Additionally, reducing carbon dioxide emissions, saving money on energy bills, and demonstrating environmental commitment and innovativeness have been identified as drivers of household adoption for microgeneration heat technologies in the UK context [315,316], whereas barriers include financial concerns, and uncertainties over performance and reliability.

[66] The most represented year in the review period was 2016 (N = 21), compared to a mean of 9 articles for the search period.

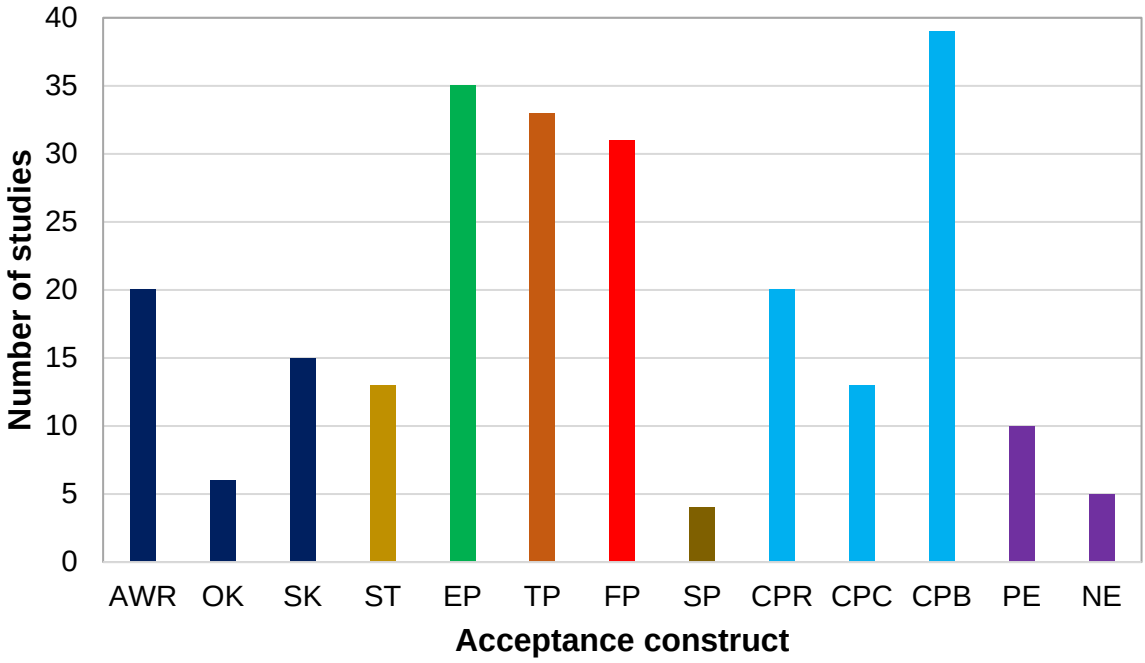


Fig. 2-12. Technology acceptance constructs across domestic energy studies (N = 42).

AWR = Awareness; OK = Objective Knowledge; SK = Subjective Knowledge; ST = Social Trust; EP = Environmental Perceptions; TP = Technological Perceptions; FP = Financial Perceptions; SP = Safety Perceptions; CPR = Comprehensive Perceived Risks; CPC = Comprehensive Perceived Costs; CPB = Comprehensive Perceived Benefits; PE = Positive Emotions; NE = Negative Emotions.

Dark blue = Cognitive Processes; Gold = Social Trust; Green = Environmental Perceptions; Orange = Technological Perceptions; Red = Financial Perceptions; Brown = Safety Perceptions; Light blue = Perceived Effects (Risks, Costs, Benefits); Purple = Emotional Response (Positive Emotions, Negative Emotions).

2.4.3 Comparative analysis of energy acceptance literatures

2.4.3.1 Insights from bibliometric analysis

Following the structured analysis of acceptance for hydrogen and domestic energy technologies, the two datasets were merged in VOSviewer, with the aim of validating previous observations and detecting critical relationships. A total of 268 keywords were processed from the final dataset (N = 75), resulting in 45 connected keywords with the minimum number of occurrences set to two. Following the structure of this analysis, Fig. 2-13 provides a network visualisation to support the summary analysis, while Fig. 2-14 presents a density visualisation, wherein keywords are clearly highlighted for improved readability of results.

In total, eight clusters were formed ranging from five to seven items. Notably, various representations of ‘acceptance’ emerge from the visualisation, including ‘consumer

acceptance' and 'public acceptability' (Cluster 1, red), 'social acceptance' (Cluster 2, green), 'public acceptance' (Cluster 3, dark blue), 'technology acceptance' (Cluster 4, yellow; Cluster 5, purple), and 'willingness to adopt' (Cluster 8, brown). This observation reflects scholarly debate regarding the fuzziness of acceptance terminologies within the literature [317,318], which has led to calls for clearer demarcation [58,244,319].

The affective dimension of technology acceptance is represented by 'emotions' and 'affect' (Cluster 1; Cluster 7, orange), reinforcing the relevance of this often overlooked construct. Additionally, Cluster 6 (light blue) includes 'environmental concern', which registers directly to the environmental perceptions construct, with an explicit emotional connotation. Cluster 3 captures 'consumer behaviour' while Cluster 5 includes 'consumer attitude', thereby highlighting the behavioural and attitudinal acceptance dimensions, which are also represented elsewhere via 'ecological lifestyle' and 'product knowledge' (Cluster 6), with Cluster 7 including an additional behavioural component via 'social practices'. Critically, risk perceptions and perceived benefits feature in Clusters 1 and 3, validating the relevance of the perceived effects construct.

The socio-political level is reflected by 'energy policy' (Cluster 4), while market acceptance is denoted in terms of 'purchase intention' (Cluster 6) and 'willingness to pay' (Cluster 8). However, consistent with patterns observed in Fig. 2-3 and Fig. 2-8, the community acceptance dimension remains obscured when mapping the relationship between keywords. In addition to displaying specific technologies from both contexts across various clusters, the visualisation entails a specific theoretical component in Cluster 8 vis-à-vis the Theory of Planned Behaviour, which is connected to 'structural equation modelling' (SEM) and 'consumers', alongside 'willingness to pay' and 'willingness to adopt'.

As an extension of traditional linear regression modelling techniques, otherwise referred to as the 'second generation' of multivariate analysis [320], SEM provides a flexible technique [321] for explaining "multiple statistical relationships simultaneously through visualisation and model validation" [322]. Consequently, SEM has been widely adopted by researchers across the social sciences [323–326], with notable proliferation among energy acceptance scholars in recent years [71,263,327–329].

SEM featured in approximately 45% of the reviewed studies (N = 34), with a somewhat stronger representation within domestic energy acceptance studies (N = 21, ~47%) compared to hydrogen acceptance studies (N = 13, ~39%). For the most part, the remaining studies employed a range of regression analysis techniques [330]. The implications of employing respective SEM techniques (CB-SEM and PLS-SEM) are further explored in Appendix L (see Fig. L-6), reflecting the need for a deeper exploratory focus on advancing theories of domestic hydrogen acceptance.

2.4.3.2 Insights from theoretical engagement and coverage of acceptance dimensions

In view of theoretical approaches, hydrogen acceptance studies present somewhat divergent trends compared to the literature on domestic energy acceptance. Foremost, DoI theory is absent from the hydrogen dataset, although associated constructs may be subsumed within TAM and other models at times. Nevertheless, this finding is significant in demonstrating a deficiency in considering critical acceptance factors linked to perceived technology attributes, such as relative advantage and compatibility. Accordingly, it would follow that the market acceptance dimension is more overlooked within the hydrogen acceptance literature, which is corroborated by Fig. 2-15.

The combined prominence of the TAM and SETA model within the domestic energy acceptance literature (38.3%), compared to the hydrogen acceptance dataset (25.8%), may explain the disparity between engagement with behavioural acceptance (see Fig. 2-15). By contrast, socio-psychological theories feature much more prominently in the hydrogen acceptance literature (54.3%) compared to the domestic energy dataset (33.3%). Consequently, there is less diversity regarding theoretical application across hydrogen studies, although the more recent uptake of the TSA and 5D-DHAF partially offset this imbalance. Overall, these trends support the critical need for a more unified approach to the study of hydrogen acceptance, especially in the context of domestic energy technologies, which can be achieved by developing an integrated framework.

Hydrogen studies also had less variance in terms of engagement across available acceptance dimensions (*SD* = 4.0) compared to domestic energy studies (*SD* = 9.0). This trend is reflected by the hydrogen group having a comparatively lower representation across four dimensions (~46.9%) compared to the domestic energy

group (~57.1%). Furthermore, the hydrogen sample was characterised by both weaker and stronger levels of engagement with the 5D-DHAF, following a higher frequency for engaging with two dimensions (~18.8%) and five dimensions (~21.9%) compared to domestic energy studies (~9.5% and 16.7%). However, the two datasets proved comparable when considering engagement across three acceptance dimensions (Hydrogen energy = ~15.6%; Domestic energy = ~16.7%).

It may be concluded that hydrogen researchers are more likely to maximise engagement across the 5D-DHAF, whereas domestic energy researchers have a slightly stronger tendency to interact with at least four dimensions (73.8% compared to 68.8%). Encouragingly, the combined sample shows advancement towards engaging with a more multi-dimensional approach to energy acceptance than envisioned within the TSA. Nevertheless, significant scope exists for consolidating research efforts towards capturing a fuller representation of technology or social acceptance, as conceptualised within the 5D-DHAF.

The lack of engagement across the 5D-DHAF can be traced to four dimensions, whereas attitudinal acceptance is a prerequisite of understanding consumer response to energy technologies. Across the sample, socio-political (*M* = 83.2) and behavioural acceptance (*M* = 81.3) are represented most frequently behind attitudinal acceptance. However, as highlighted, hydrogen energy acceptance studies are more likely to integrate a socio-political lens (*M* = 87.9), while domestic energy acceptance studies usually include a behavioural focus (*M* = 92.9), which is significantly less common among hydrogen researchers (*M* = 69.7). The market acceptance dimension ranks next (*M* = 73.5) with higher representation among domestic energy studies (*M* = 83.3), while community acceptance is the most underexplored dimension (*M* = 38.5).

To an extent, hydrogen acceptance researchers may leverage lessons from domestic energy studies when seeking to elevate engagement in behavioural and market acceptance dimensions. Conversely, domestic energy acceptance scholars may learn from their hydrogen counterparts when striving to engage more actively with community-level factors. Nevertheless, both research strands are yet to consistently explore community acceptance factors, which emerges as an outlier within this analysis. Through the process of an integrated, comparative review grounded in systematic methods, research deficits at the theoretical level have been expounded

through a novel approach, which can be elaborated on or otherwise replicated in future studies.

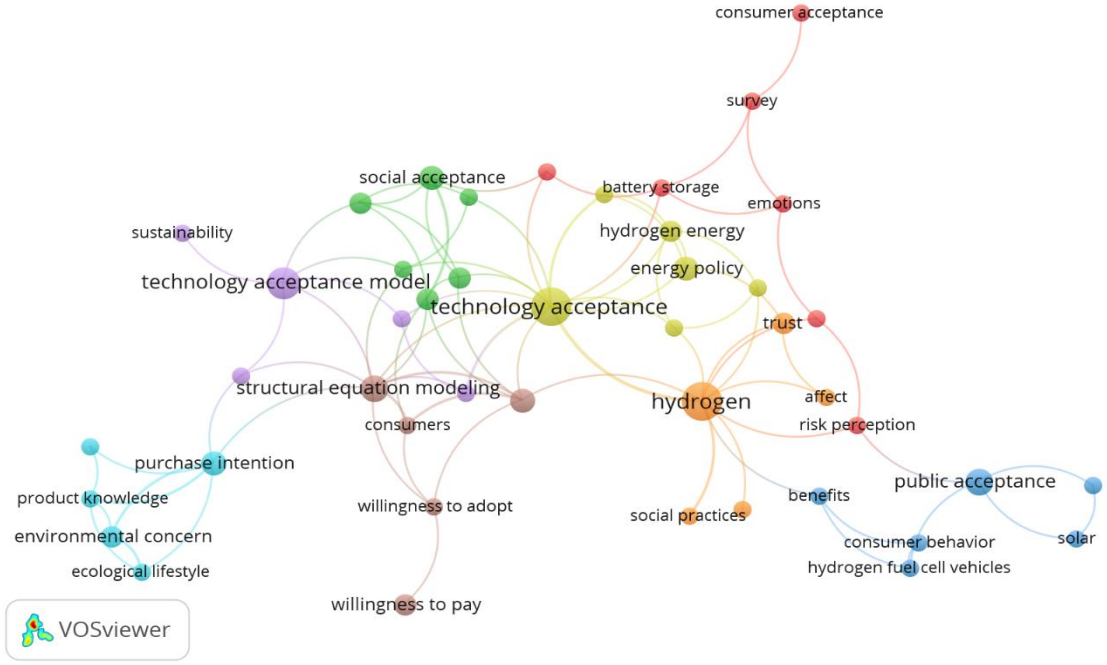


Fig. 2-13. Network visualisation of connected keywords in dataset (N = 75).

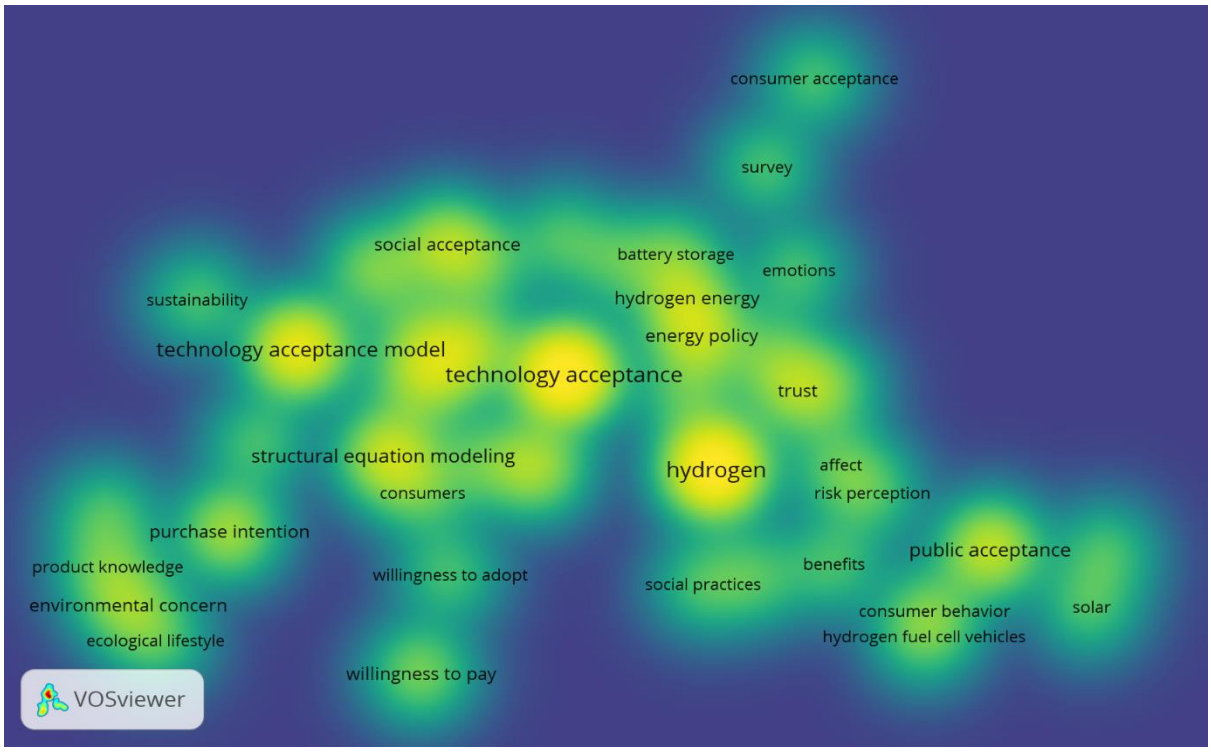


Fig. 2-14. Density visualisation of connected keywords in dataset (N = 75).

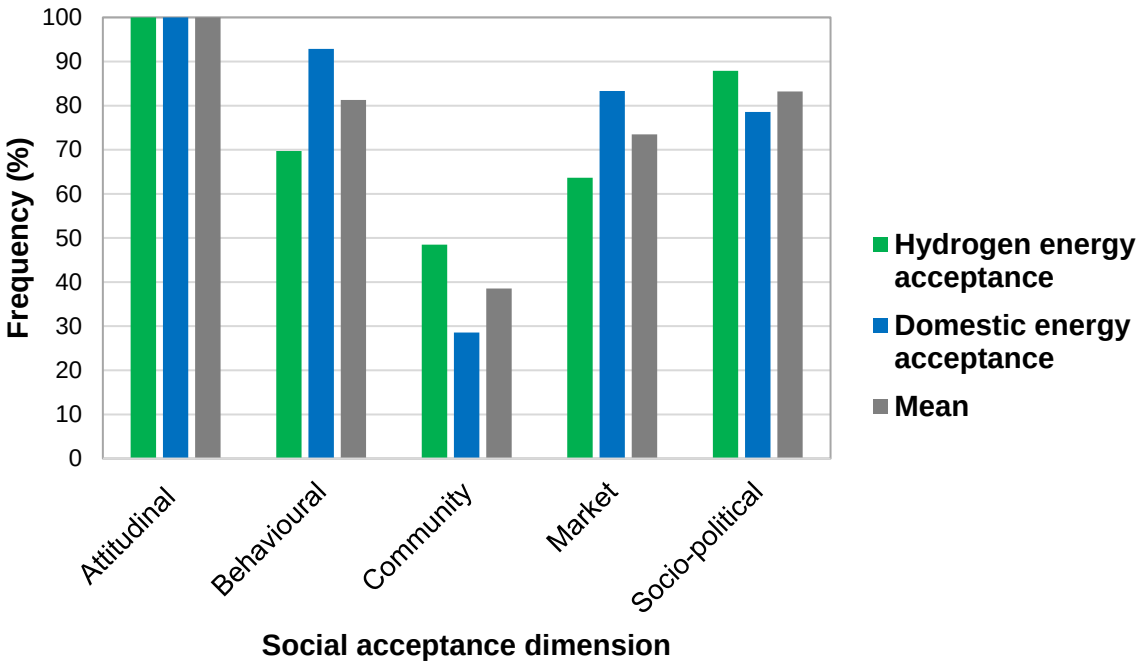


Fig. 2-15. Comparative analysis of engagement in social acceptance dimensions across sample (N = 75).

2.4.4 Insights from integration of acceptance constructs

Several key insights can be extracted from comparing the use of acceptance constructs across the respective datasets, as presented in Fig. 2-16. Both research strands present comparable engagement with the environmental perceptions (ENV: *M* = 84.1) and awareness constructs (AWR: *M* = 48.1). Notably, environmental perceptions ranks first across the sample, whereas awareness ranks sixth, albeit ahead of both subjective knowledge (SK: *M* = 40.6) and objective knowledge (OK: *M* = 17.7), which rank ninth and last (13th) respectively. Consequently, knowledge-related aspects are significantly underexplored compared to awareness, although subjective knowledge is more commonly examined within hydrogen studies (*M* = 45.5).

Fig. 2-16 shows that hydrogen studies present a higher comparative representation across most acceptance constructs, with three notable exceptions: technological perceptions (-21.3 for hydrogen studies); financial perceptions (-22.2 for hydrogen studies); and comprehensive perceived benefits (-14.2 for hydrogen studies). The identified factors rank second (CPB: *M* = 82.8), third (TP: *M* = 63.5), and fifth (FP: *M* = 58.1) across the sample, reinforcing critical opportunities to support the “social science research agenda for hydrogen transitions” [26]. As a result, insights from domestic energy acceptance studies can be directly leveraged to advance hydrogen

research in the context of home heating and cooking appliances, through a stronger focus on perceived benefits, alongside technology and financial perceptions. Nevertheless, hydrogen acceptance researchers tend to engage more with perceived risks, and less with perceived costs, as compared to perceived benefits, therefore, a stronger balance of representation is needed across associated measures of perceived effects.

While the highlighted constructs warrant increased attention in view of their prevalence within domestic energy studies, the overall results stress the need to increase research engagement across multiple acceptance dimensions. Foremost, more extensive insights are needed regarding socio-psychological variables such as knowledge, awareness, and trust, in addition to emotional factors. Furthermore, the emotional spectrum should be explored in relation to specific drivers such as risk perceptions.

Corroborating these observations, Fig. 2-17 emphasises a predominantly slow uptake regarding efforts to operationalise multiple acceptance constructs within studies. While the sample (N = 58) is restricted to seven years,[67] there is no strong evidence of overall growth, although hydrogen acceptance studies have performed significantly better within the last two recorded years (see Table L-8).

As a broad guideline, it is recommended that acceptance studies engage with at least 8 of the 13 constructs measured in this review, which has only occurred within a single year for one technology (hydrogen acceptance studies in 2022: *M* = 8.8). While an outlier in this study, this metric reflects the direction in which energy acceptance research should rapidly move for deriving more comprehensive and critical insights on consumer perspectives. The final section synthesises the presented evidence by constructing a new model, which can be adapted and extended in future work to consolidate a Unified Theory of Domestic Hydrogen Acceptance.

[67] 2017 is taken as a start year, since 2017 and 2018 are first consecutive years in which at least two studies for each dataset were retrieved for the SLR.

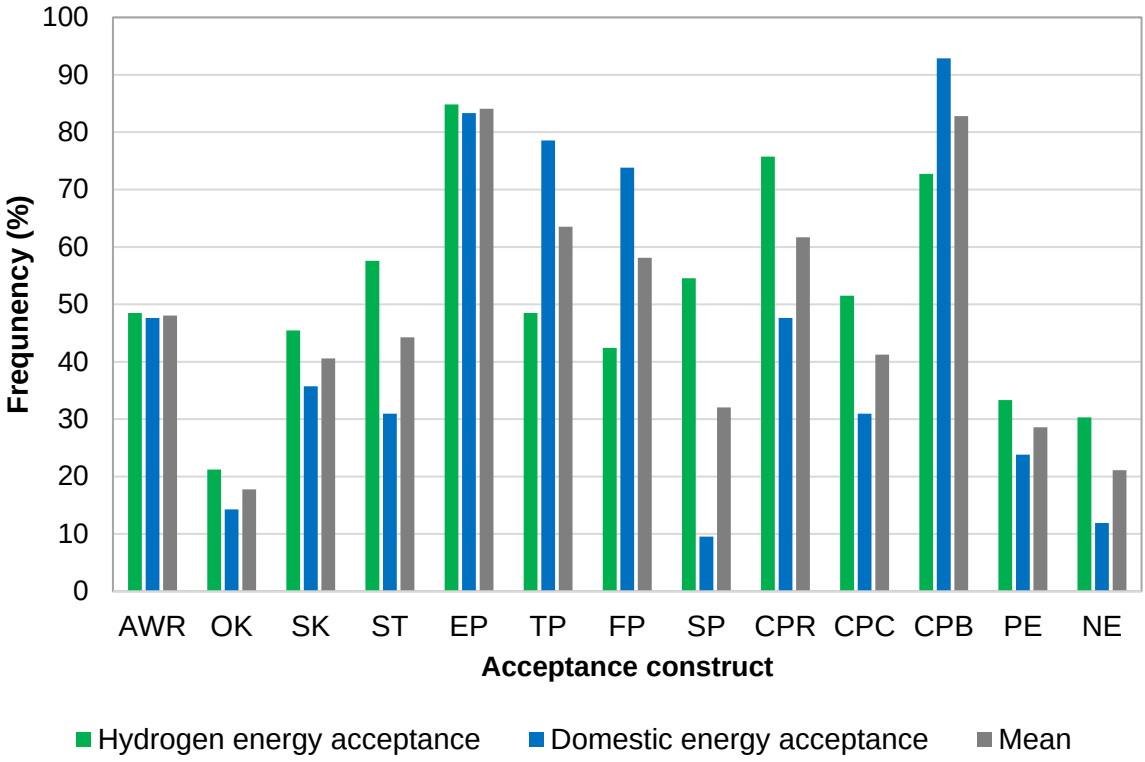


Fig. 2-16. Comparative analysis of engagement in technology acceptance constructs across sample (N = 75).

AWR = Awareness; OK = Objective Knowledge; SK = Subjective Knowledge; ST = Social Trust; EP = Environmental Perceptions; TP = Technological Perceptions; FP = Financial Perceptions; SP = Safety Perceptions; CPR = Comprehensive Perceived Risks; CPC = Comprehensive Perceived Costs; CPB = Comprehensive Perceived Benefits; PE = Positive Emotions; NE = Negative Emotions.

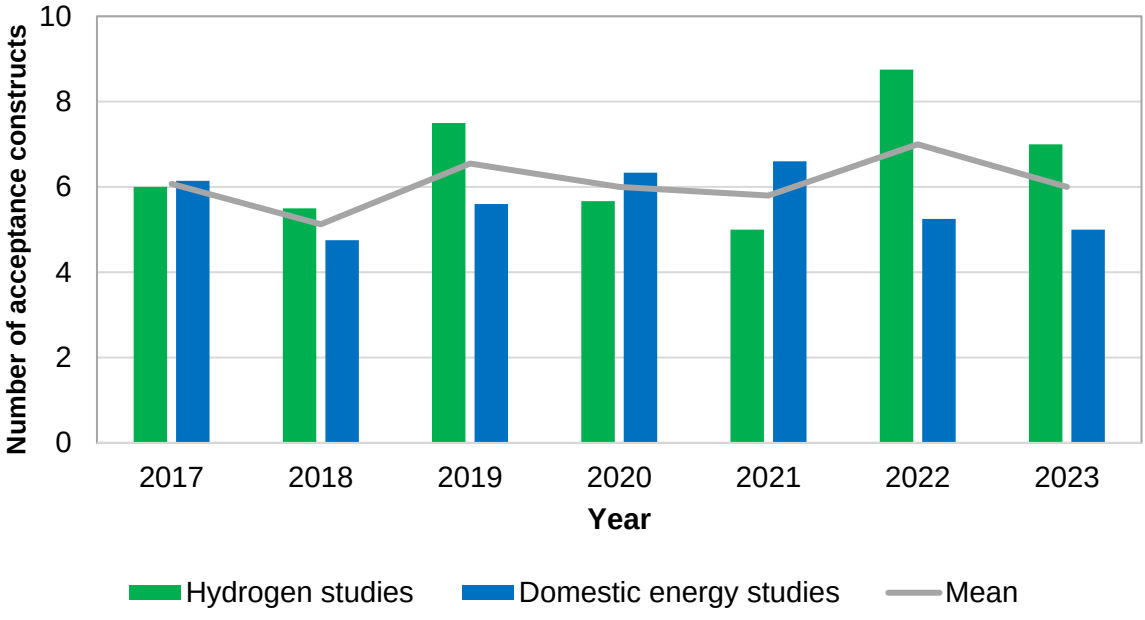


Fig. 2-17. Engagement with acceptance constructs, 2017–2023.

2.5 Towards a unified theory of domestic hydrogen acceptance

2.5.1 Theoretical foundations of the proposed framework

Through a novel operationalisation of traditional and emergent technology acceptance constructs, Fig. 2-18 synthesises a range of critical theories to establish a unified theory of domestic hydrogen acceptance. The proposed framework reflects the importance of linking established acceptance constructs such as knowledge and awareness [150] to emotional response, as specified by Kulviwat et al. [89] in the CAT model. Specifically, the CAT model argues that a multi-dimensional focus is essential to reflect scenarios in which technology adoption is a choice, as opposed to being mandated, wherein consumers arrive to their decisions through both cognitive and emotional processes [89]. This framing is noteworthy to the case of hydrogen homes, wherein households may choose to install electric alternatives such as heat pumps and induction hobs [44,292], thereby potentially defecting from a transition to hydrogen appliances following local grid conversion [56].

Similarly, the unified theory incorporates the fundamentals of DoI [150] by directly modelling technological perceptions, reflecting the importance of this construct in the context of domestic energy acceptance [79]. In conjunction, the proposed framework can be characterised as an expectancy-value model [190], since it captures performance expectations for hydrogen boilers and hobs, thereby resonating with the TPB. Additionally, consumer expectations across environmental, financial, and safety dimensions are incorporated into the framework.

Notably, by including environmental perceptions as an exogenous construct, the framework internalises elements of Stern's VBN theory [331] such as normative beliefs about climate change [205]. Such beliefs have been shown to evoke emotional responses to sustainable energy innovations [332] such as heat pumps [333]. The framework also leverages from UTAUT2 [218] by incorporating financial perceptions as an antecedent of comprehensive perceived effects (i.e. risks, costs, and benefits).

Fundamentally, the unified theory proposed in Fig. 2-18 presents a combined, integrated model, thereby following in the tradition of Taylor and Todd as captured in the Combined TAM and TPB (C-TAM-TPB) [196], and associated multi-dimensional approaches to modelling technology acceptance [189,229,243,334]. Through this focus, the potential diffusion of domestic hydrogen technologies is influenced by

dynamic interactions between acceptance constructs [58,82], in conjunction with other critical drivers such as political and techno-economic factors [6,59]. Notably, Frankhauser et al. [335] recently highlighted the need to navigate between “political, economic, legal and behavioural” dimensions to support net-zero ambitions, which is reflected via the explicit focus on consumer behaviour put forward in this study.

While the 5D-DHAF specifies that cognitive legitimacy is a prerequisite for facilitating behavioural acceptance, as realised through the adoption of hydrogen home appliances; the unified theory extends the framework by integrating emotional valence [287,336] into the equation of prospective technology acceptance. Through this lens, the presented framework is cognisant of the potential effects of emotions on technology acceptance and adoption [337], taking stock of prior efforts to develop an ‘emotional-TAM’ in other contexts [338]. Notably, appraisal theory posits that specific emotions arise because of one’s cognitive and affective appraisal of a situation [339]. As a critical contribution to the social science research agenda on the hydrogen economy [26,340], this analysis reflects the premise that energy acceptance and subsequent adoption are shaped via an interplay between rational thought and emotional response [81,259], as depicted in Fig. 2-18.

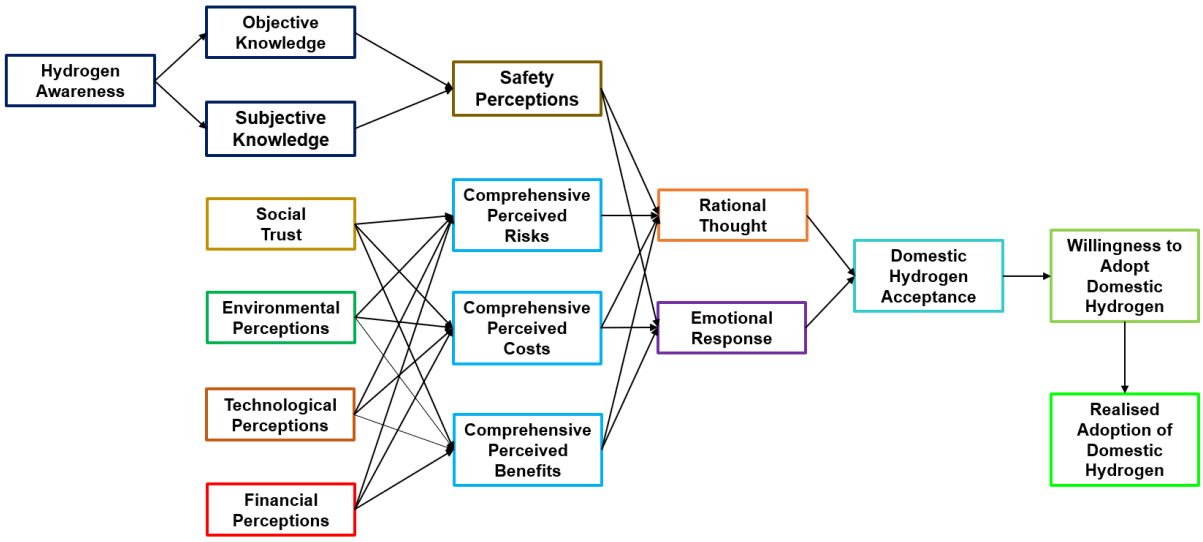


Fig. 2-18. The unified theory of domestic hydrogen acceptance.

Dark blue = Cognitive Processes (Hydrogen Awareness, Objective Knowledge, Subjective Knowledge); Gold = Social Trust; Green = Environmental Perceptions; Dark Orange = Technological Perceptions; Red = Financial Perceptions; Brown = Safety Perceptions; Light blue = Perceived Effects (Risks, Costs, Benefits); Orange = Rational Thought; Purple = Emotional Response; Teal = Domestic Hydrogen Acceptance; Light green = Willingness to Adopt Domestic Hydrogen; Bright green = Realised Adoption of Domestic Hydrogen.

2.5.2 Hypothesised relationships within the model

The proposed model consists of 13 constructs, which are hypothesised to predict domestic hydrogen acceptance, in turn predicting willingness to adopt domestic hydrogen appliances and subsequent technology adoption (see Table 2-4). Critically, compared to the SETA model (see Fig. L-4 and Fig. L-5), several changes and adaptations are implemented to reflect the technology-specific context of hydrogen homes as outlined in Section 2.4.1.2 (see Table L-5).

Whereas the SETA model has its foundations in two seminal theories, namely the NAM (1977) and TPB (1985), the unified theory of domestic hydrogen acceptance draws additional inspiration from DoI theory, the TAM, UTAUT, TSA, and 5D-DHAF. Notably, in addition to social trust, the model integrates environmental, technological, and financial perceptions as antecedents of (comprehensive) perceived effects (risks, costs, and benefits) to reflect the context of low-carbon residential technology acceptance and adoption.

Contrary to the SETA, emotional response (i.e. positive affect and negative affect) is predicted by comprehensive perceived effects, while safety perceptions is introduced to reflect the sensitive, residential context of the domestic hydrogen transition (see Section 2.5.2.1). Additionally, model parsimony is improved compared to the SETA by reducing the number of direct predictors of behavioural intention (i.e. social normal, perceived behavioural control, attitude, and personal norm), whereby the causal chain of domestic hydrogen acceptance and adoption intention can be traced to rational thought and emotional response (see Section 2.5.2.6).

In total, five exogenous constructs are included in the model: (hydrogen) Awareness (AWR); Social Trust (ST); Environmental Perceptions (EP); Technological Perceptions (TP); and Financial Perceptions (FP). Objective Knowledge (OK) and Subjective Knowledge (SK) are hypothesised to mediate the relationship between AWR and SP. Therefore, AWR has direct effects on both types of knowledge. The remaining exogenous constructs have direct effects on Comprehensive Perceived Effects (CPE), composed of perceived risks (CPR), costs (CPC), and benefits (CPB).

In summary, when ST is weaker, and EP, TP, and FP are negative, consumers are more likely to perceive higher risks and costs associated with the domestic hydrogen transition and the introduction of hydrogen home appliances. Conversely, CPB will

stem from positive environmental, technological, and financial perceptions, alongside stronger levels of social trust. Critically, a distinction is drawn between FP, which entails expectations regarding purchasing and running costs for hydrogen homes, and CPC, which relates to broader economic, as well as social and environmental costs.

Similarly, safety perceptions and perceived risks are modelled separately, in view of the anticipated importance of safety factors to household decision-making. For example, Scott and Powells [26,27] identified safety perceptions as an important aspect of domestic hydrogen acceptance, which has been validated in follow-up studies in the UK context [292,341]. Notably, national survey results from Australia found safety to be the most important factor in determining consumer willingness to use domestic hydrogen, while reliability of energy supply ranked second [342].[68] Consequently, in contrast to safety perceptions, perceived risks are characterised primarily in terms of concerns over disruptive impacts. Perceived disruptive impacts may extend from the street-level to the community-level, thereby entailing potential socio-economic and health risks to both households and local communities [28].

While there is a natural interplay between perceived risks and costs, the former is more strongly linked to anticipated issues associated with infrastructure development, while the latter corresponds to more tangible impacts which may be quantified, such as potential job or income loss. For example, in reference to perceived costs, Scovell and Walton [115] discuss the potential impacts of hydrogen technologies on energy security and supply, and market implications linked to competition with renewable energy technologies.

In turn, CPR, CPC, and CPB influence both cognitive attitudes and affective evaluations, as reflected by Rational Thought (RT) and Emotional Response (ER) within the model, whereby ER is derived in relation to measures of Positive Emotions (PE) and Negative Emotions (NE). Together, RT and ER influence Domestic Hydrogen Acceptance (H2-ACPT), which predicts Willingness to Adopt Domestic Hydrogen (WTA-H2). Similarly, SP predicts H2-ACPT, as mediated by RT and ER. Accordingly, domestic hydrogen acceptance is shaped by rational thought and emotional response, thereby merging the cognitive and affective dimensions of human decision-making.

[68] See Table 16 in Martin et al. [342] for a comparison of results from 2018 and 2021 wherein safety ranked first in both cases ahead of factors such as reliability of energy supply, fuel costs, the cost to modify appliances, and moreover, elimination of greenhouse gas emissions.

Finally, adoption potential is hypothesised to predict the scope for purchasing domestic hydrogen appliances, which is referred to as Realised Adoption of Domestic Hydrogen (RA-H2) in this study.

Table 2-4. Proposed hypotheses within the unified theory of domestic hydrogen acceptance.

Hypotheses	Relationship between acceptance constructs
H1a, H1b	Awareness (AWR) → Knowledge (*OK; SK*)
H2a, H2b	Knowledge (*OK; SK*) → Safety Perceptions (SP)
H3a–H3c	Social Trust (ST) → Comprehensive Perceived Effects (*CPR*, *CPC*, *CPB*)
H4a–H4c	Environmental Perceptions (EP) → Comprehensive Perceived Effects (*CPR*, *CPC*, *CPB*)
H5a–H5c	Technological Perceptions (TP) → Comprehensive Perceived Effects (*CPR*, *CPC*, *CPB*)
H6a-H6c	Financial Perceptions (FP) → Comprehensive Perceived Effects (*CPR*, *CPC*, *CPB*)
H7a, H7b	Safety Perceptions (SP) → Emotional Response (*PE; NE*)
H8	Safety Perceptions (SP) → Rational Thought (RT)
H8a–H8f	Comprehensive Perceived Effects (*CPR*, *CPC*, *CPB*) → Emotional Response (*PE; NE*)
H9a–H9c	Comprehensive Perceived Effects (*CPR*, *CPC*, *CPB*) → Rational Thought (RT)
H9a, H9b	Emotional Response (*PE*; *NE*) → Domestic Hydrogen Acceptance (H2-ACPT)
H10	Rational Thought (RT) → Domestic Hydrogen Acceptance (H2-ACPT)
H11	Domestic Hydrogen Acceptance (H2-ACPT) → Willingness to Adopt Domestic Hydrogen (WTA-H2)
H12	Willingness to Adopt Domestic Hydrogen (WTA-H2) → Realised Adoption of Domestic Hydrogen (RA-H2)

2.5.2.1 Knowledge, awareness, and safety perceptions

Firstly, the framework hypothesises that awareness of hydrogen increases both objective and subjective hydrogen knowledge, which in turn influence safety perceptions. Prior studies suggest the combined effect of higher awareness and knowledge is associated with more positive hydrogen safety perceptions [343], which increases the likelihood of consumer acceptance [344]. However, with higher objective knowledge, safety concerns may also become elevated in view of hydrogen's psychical and chemical properties [326].

Critically, safety challenges will be elevated in the context of residential hydrogen [59] as opposed to industrial use [18]. Hydrogen's distinct physical and chemical properties may give rise to negative safety perceptions [27], which could translate into feelings

of fear and anxiety [345]. In various contexts, the explosive risks of hydrogen have been consistently highlighted by survey respondents [295,346–348], whereas safety benefits are less frequently cited [345], although neutral perceptions may also prevail [26]. Notably, consumers perceive greater safety risks regarding hydrogen cooking compared to hydrogen heating [27,292].[69] Evidence further suggests a more positive safety perception of induction hobs compared to gas cookers and prospective hydrogen hobs [292]. Additionally, fears may stem from risks associated with the underground storage of hydrogen [349,350].

For much of society, domestic hydrogen may evoke a range of positive or negative emotions linked to safety perceptions. On the one hand, the public may expect the new technology to have undergone stringent safety checks if approved for deployment [47,351]. Such perceptions could potentially ease safety concerns and instil a sense of consumer confidence [26,47,351]. Furthermore, in countries such as the UK, hydrogen may be perceived positively for eliminating the risk of carbon monoxide poisoning within the home [352]; especially among households experiencing fuel poverty where the risk is disproportionately higher [352]. However, general or specific concerns regarding the flammability of hydrogen [353], alongside other hazardous risk factors [354–356], could instead evoke feelings of fear and anxiety among consumers [27,345].

The proposed framework hypothesises that dependent on the given consumer profile and situational context (e.g. family household vs single household), the causal chain between awareness and knowledge levels, safety perceptions, and emotional response is likely to be activated. Thus, a positive or negative association to safety may be observed according to the sample in question, wherein the technical knowledge level of lay respondents is likely to shape the observed relationship. As noted by Beasy et al. [357], technical knowledge may counteract negative safety perceptions. Critically, as technical knowledge increases, there is stronger likelihood that consumer attitudes will stem primarily from cognitive evaluations, as opposed to affective response.

[69] This divergence is attributed to hobs actively shaping the lived experience of domestic energy, whereas boilers are usually concealed or more passively experience [27].

2.5.2.2 Social trust and comprehensive perceived effects

Social trust is a complex, multi-dimensional construct [358], which can be explored in terms of both cognitive and emotional dimensions [157,359], alongside specific areas such as institutional trust [360,361]. At the cognitive level, a further distinction can be made between 'competence-based' and 'integrated-based' trust [157,362]. Notably, in the Australian context, support for developing a national hydrogen economy was associated with social trust in the commitment and ability of government and industry towards tackling decarbonisation [239]. In the German context, Häußermann et al. [48] concluded that "acceptance of green hydrogen relies on trust in science, government, the media, and institutions that uphold distributive justice."

Regarding emerging energy technologies such as hydrogen, a deficit in social trust may elevate perceptions of risks and costs; whether at the macro-level, community-level, or household-level, thereby undermining the potential for social acceptance and subsequent adoption [291]. Accordingly, social trust is critical to ensuring that perceptions of potential benefits outweigh the combined negative effect of perceived risks and costs, which may prove challenging during the formative stage of technology diffusion when uncertainties accrue [363].

2.5.2.3 Environmental perceptions and comprehensive perceived effects

Attitude towards climate change, green consumption and related environmental aspects are anticipated to shape perceived effects of hydrogen technologies [274,275]. Foreseeably, if the low-carbon credentials of domestic hydrogen are supported, especially among consumers considering themselves to be conscious of climate change issues, perceived environmental benefits will be the logical outcome [341,345]. However, environmental perceptions may prove negative when adverse impacts are anticipated, such as air pollution [364,365], increased water scarcity, or land spoilage [47,82,115].

Critically, 'blue' hydrogen production relies on steam methane reformation and CCS [366], which could give rise to environmental opposition due to reliance on natural gas [59,367,368]. Additionally, public resistance may develop due to potential resource scarcity and energy injustices associated with the mining of critical materials for green hydrogen production via electrolysis [369,370]. Accordingly, environmental perceptions may also contribute directly to a mix of perceived costs and risks linked to

socio-economic impacts. Nevertheless, in the German context, Hoffmann and colleagues [371] demonstrated that German respondents express higher support for green hydrogen when the focus is solely on the benefits of climate protection, as opposed to energy security and climate protection.

2.5.2.4 Technological perceptions and comprehensive perceived effects

The motivations, behaviours, and decisions of consumers depend on perceptions of specific technology attributes, and whether the totality of these attributes offers a relative advantage over the incumbent technology [81,271,372,373]. However, technological perceptions are yet to be clearly demarcated in the context of hydrogen homes. Drawing on Rogers' DoI [150], Table 2-5 provides a starting point for comprehensively examining technological perceptions, in view of the implied temporal dynamics of transitioning to hydrogen homes.

Table 2-5. Technology attributes influencing domestic hydrogen acceptance.

Perceived technology attribute	Explanation in the context of domestic hydrogen
Relative advantage	• Consumer perceptions regarding the potential advantages of domestic hydrogen over the incumbent technology (i.e. natural gas appliances)
Complexity	• Consumer perceptions regarding the ease of operation and effort levels associated with the use of hydrogen boilers and hydrogen hobs
Compatibility	• Consumer perceptions regarding the fluidity or level of equivalence of hydrogen appliances to the existing socio-technical regime, in relation to both the techno-economic (i.e. infrastructural) and behavioural (i.e. socio-cultural) sides of the transition
Trialability	• The degree to which hydrogen appliances may be experimented with and experienced by consumers on a limited basis prior to potential adoption
Observability	• The level to which tangible gains are visible and perceptible for others

Source: Authors' compilation based on [150,189].

Currently, hydrogen demonstration projects are anticipated in countries such as the UK within the coming years; commencing with trials for a few hundred homes if approved by the government [51,374,375]. To date, opportunities for experimentation by the public have been mostly limited to select project sites such as the Hydrogen Experience Centre in Ellesmere Port, Northwest England [376]. However, the planned trial for Whitby village was cancelled in July 2023 following local opposition, which has

setback opportunities to increase the trialability and potential observability of hydrogen homes [377,378].

The status quo of hydrogen energy technologies, especially in the domestic context, may give rise to negative attitudes due to perceptions of technological uncertainty and risk. However, should hydrogen appliances be perceived to have an inherent relative advantage over their natural gas counterparts, technological perceptions would prove more positive and strengthen perceived benefits [292]. Perceptions of relative advantage may stem from expectations for better performance in terms of energy efficiency, or link to improved ease-of operation in terms of smart performance and reduced maintenance [292]. At the same, non-functional advantages such as pleasing aesthetics related to product design and materials could potentially increase positivity around hydrogen home appliances.

Consequently, technological perceptions will be shaped by various components related to perceived relative advantage, including performance and effort expectancy, as well as compatibility with existing infrastructure [59] and lifestyles [27] (see Table 2-5). Technological perceptions will also hinge on risk averseness to changing one's home environment, alongside individual propensity for being an early adopter. As noted by Tran et al. [379] in the context of HFCVs and other alternative vehicles, early adopters may be motivated by a mix of environmental, technological, and financial perceptions, resulting in significant consumer heterogeneity.

2.5.2.5 Financial perceptions and comprehensive perceived effects

It is highly feasible that micro-economic considerations may largely dictate domestic hydrogen adoption among most households, particularly during times of economic crisis and high energy bills [380]. Accordingly, financial perceptions regarding the purchasing and running costs of hydrogen appliances, as well as potential monetary impacts related to maintenance requirements [26,28], will also inform the balance between comprehensive perceived effects for a given consumer.

Given the potential scope for undertaking cost-benefit analysis, financial perceptions are anticipated to link more strongly to the rational decision-making dimension of domestic hydrogen acceptance. However, under conditions of economic stress and uncertainty, perceptions of potential financial loss could evoke feelings of anxiety and fear, which in turn influence attitudes and market behaviour. Additionally, certain

consumer segments may be significantly less predisposed to enacting formal or quasi-calculations in the domain of energy appliances, which would render the decision more intuitive and emotive, as opposed to reasoned and rational.

To some extent, consumers may expect to incur additional costs if upgrading to higher performing appliances and could potentially accept these costs if predisposed to being early adopters [291]. Early adopters, who often hold pro-environmental attitudes [381,382], may prove more likely to accept a premium for switching to low-carbon home appliances. In such a scenario, negative perceptions of financial impacts may be partially offset due to a positive cost-benefit appraisal linked to environmental benefits [341]. By contrast, for consumers making up the early or late majority of adopters [150], financial perceptions may align more strongly to the negative side of perceived effects, especially when fuel poverty risks are imminent.

Negative perceptions would also prove more dominant if the relative advantage of hydrogen technologies is not substantiated, or under conditions where alternative technologies such as heat pumps and induction hobs succeed in outperforming hydrogen appliances, while also proving price competitive. As a result, financial perceptions and associated willingness-to-pay for domestic hydrogen will reflect both normative beliefs [275] and market dynamics [59,291], in addition to one's specific economic status at a given point in time [26].

2.5.2.6 Rational thought and emotional response

In a critical contribution to the energy acceptance literature, Michelsen and Madlener [81] examined the 'motivational factors' influencing the adoption decisions of German homeowners in the context of low-carbon residential heating systems. Through principal component analysis, the study identified 25 factors categorised to six dimensions, which see adoption motivation link to rational decision-making and emotional factors [81]. On the one hand, the framework internalised cost factors (i.e. FP) and implications of a government grant (i.e. FP, ST, CPE), which better reflect the dimension of rational thought. At the same, emotional aspects were represented by proxy in relation to comfort considerations of the technology (i.e. TP). Furthermore, cognitive and affective dimensions may be activated when reacting to external threats, such as environmental or energy supply security considerations (i.e. CPR, CPC), and safety-related risks (i.e. SP).

Interestingly, the critical review conducted by Scovell [82] draws attention to a range of salient beliefs hypothesised to influence emotional responses to hydrogen energy technologies. However, the more recent qualitative study conducted by Scovell and Walton [115] via focus group discussions with Australians reflects the potential for overlooking or obscuring 'hydrogen-related emotions'. Notably, the research angle focuses on how consumers develop 'informed beliefs about hydrogen technologies', however, the thematic analysis fails to reflect the trust dimension of attitudinal acceptance [115].

In summary, Scovell and Walton [115] identified eight categories underpinning attitudes towards hydrogen in general, which fall more strictly across the cognitive dimension of acceptance.[70] Countering this perspective, Fig. 2-18 posits that the causal chain between salient beliefs, attitudes, and behaviours cannot be decoupled from emotional response, which may include paradoxical feelings towards hydrogen homes.

Ten years on from the contribution of Michelsen and Madlener [81], few sustainability transitions scholars have attended to the emotional aspects of energy acceptance [287,332,383], rendering this dimension heavily underexplored in comparison to cognitive and perceptual factors (see Fig. 2-16). In response, Martiskainen and Sovacool [383] recently argued that certain low-carbon technologies exhibit 'emotional resonance' that exceed their functional attributes. Critically, the authors highlighted how a more explicit focus on emotional factors would challenge many established conceptual frameworks within the field of energy acceptance; calling for adaptations, extensions, and enhancements "to accommodate the potential salience of emotions" [383].

Internalising observations from different research streams (see Table 2-1) and traditions (see Table 2-2), the unified theory of domestic hydrogen acceptance posits a direct focus on cognitive beliefs and feelings [359] as the antecedents of domestic hydrogen acceptance and adoption, thereby advocating for a more integrated research approach.

[70] Uncertainty and unproven technologies (i.e. TP); safety and risk perceptions (i.e. SP and CPR); economic opportunities (i.e CPB); (in)efficiency and cost (i.e. TP, FP, CPC); (positive) environmental impacts (i.e. EP, CPB); energy security (i.e. CPB); hydrogen competing with other renewables (i.e. TP, CPC); and water use (i.e. EP, CPC).

2.6 Conclusions

This review of technology acceptance theories, and empirical studies on hydrogen and domestic energy acceptance, is motivated by the need to develop a comprehensive framework for understanding consumer behaviour in the context of hydrogen homes. As a nascent technology, the emerging contours of domestic hydrogen acceptance remain underexplored [345], while the wider literature reflects an underlying deficit in developing integrated acceptance frameworks.

Critically, the research direction has yet to shift towards a more multi-dimensional focus on domestic energy acceptance (see Fig. 2-17), as advocated for Bögel et al. [264], Elmustapha et al. [262], and most recently, Chadwick and colleagues [259]. This status quo is striking given that Venkatesh et al. [88] established the higher predictive power of operationalising an integrated model via the UTAUT some two decades ago. Moreover, the advantages of leveraging multi-dimensional conceptual frameworks have been consistently corroborated in consumer acceptance studies focused on computer technology innovation [89], smart home technologies [229,384], solar PV panels [305] and water heaters [262], and more recently, HFCVs [274], among other examples.

2.6.1 Contributions to the field of technology acceptance

In response, the primary contribution of this study is to advance a unified theory of domestic hydrogen acceptance, which can inform the foundations for empirical analysis and subsequent conceptual development. As witnessed in the evolution of technology acceptance theories (see Section 2.3), early conceptual engagement in an emerging field of inquiry can stimulate critical uptake among scholars; culminating in significant adaptations and extensions, as well as the introduction of new frameworks (see Fig. 2-2). As exemplified by historical and ongoing engagement with DoI, TPB, NAM, and TAM, among other frameworks, developing theoretical insights distinguishes academics from practitioners and consultants [385], with scope to advance the literature and yield practical implications for businesses [386,387], society [388,389], and the environment [390,391].

Foremost, the developed model accounts for a wide range of perceptual antecedents of domestic hydrogen acceptance and adoption, in addition to knowledge, awareness, and trust. These constructs are hypothesised to have causal links to both rational

thought and emotions, reflecting the cognitive and affective dimensions of social acceptance and prospective technology adoption. In addition to providing a robust starting point for future research on domestic hydrogen acceptance, the model offers in-built transferability to examine other low-carbon residential energy technologies such as heat pumps, smart appliances, and solar homes (see Table L-3 and Table L-4).

This study contributes to the literature by synthesising findings from hydrogen acceptance and domestic energy acceptance studies for the first time, while benchmarking research approaches against the 5D-DHAF to examine multi-dimensionality across studies. As a result, this analysis reinforces the call for developing and applying integrated theoretical frameworks in energy acceptance studies, while seeking theoretical and methodological pluralism where viable. Moreover, the integrated framework espoused in this study provides a direct means for increasing the predictive power of hydrogen acceptance models to support strategic decision-making residential decarbonisation.

2.6.2 Shifting the research focus towards PLS-SEM

Robust research efforts are needed to explore theories of low-carbon energy acceptance across the mix of technologies examined within this sample, which can be best supported via PLS-SEM [392,393]. As reported in Fig. L-6, 16 studies in the sample employed PLS-SEM, including nine studies published between 2022 and 2023. Notably, researchers have recently employed PLS-SEM to identify the salient constructs of consumer acceptance for HFCVs in the Indian context [274,275,289,297]. These developments signal the emerging research trajectory and motivate the need for disseminating PLS-SEM to the hydrogen research community.

As a variance-based modelling approach, PLS-SEM is well-suited to situations of high complexity where limited theory formation has been established [365], thereby serving as a ‘causal-predictive’ technique [394]. PLS-SEM offers a suite of analytical tools for advancing quantitative engagement with domestic hydrogen acceptance. Foremost, scholars can engage with the proposed framework by using software such as SmartPLS [395] to explore the antecedents of supporting or rejecting hydrogen homes; and whether consumer perspectives are shaped primarily by rational decision-making or emotions, or a combination thereof. In doing so, practitioners will be able to

test the in-sample and out-of-sample predictive power of the unified theory of domestic hydrogen acceptance, as well as specific components of the model.

Beyond assessing traditional metrics such as structural path coefficients, effect size, and predictive power, researchers can evaluate the effects (i.e. importance) and performance of indicators through an importance-performance map analysis (IMPA) [396]. For example, via the IMPA, a latent construct such as comprehensive perceived benefits (CPB) can be further evaluated in terms of its indicators, such as perceived economic, social, and environmental benefits [341]. In parallel, the mediating role of perceived effects (i.e. CPR, CPC, CPB) and other constructs (e.g. OK, SK) can be tested to validate whether the model supports full mediation, partial mediation, complementary partial mediation, competitive partial mediation, or no mediation [397,398].

Additionally, Dul [399] developed necessary condition analysis (NCA) as methodology for identifying the necessary conditions for achieving a target outcome.[71] By integrating NCA into PLS-SEM analyses, researchers can "identify the ('must-have') factors required for an outcome, that is necessity logic, as well as the ('should-have') factors that contribute to a high-level, namely additive sufficiency logic" [400]. The practical implications of NCA are substantial in promoting more actionable insights for policy makers and stakeholders [400], which can be understood alongside results from IMPA [401].

Above all, NCA provides a direct means for verifying which acceptance/adoption constructs may presents bottlenecks [399,402] for supporting the deployment of hydrogen homes. Critically, the research community should internalise these suggestions with a view to comparing the predictive capabilities [403] of different hydrogen acceptance and adoption models via PLS-SEM, alongside complementary tools such as machine learning [404,405] and artificial neural networking [406,407].

Finally, data triangulation via mixed-methods analysis [408] can help support a more holistic assessment of the salient factors of domestic hydrogen acceptance [82,115]. By leveraging quantitative insights from qualitative datasets [409–411], results from the SLR conducted in this study (see Fig. 2-16) can be empirically validated to develop

[71] The method was originally discussed in the organisational context wherein determinants such as resources and efforts can drive a goal such as better company performance [399].

a typology of domestic hydrogen acceptance. As a proven method in the fields of psychology and sociology [412], acceptance typologies (i.e. hierarchical grouping of data into categories of importance) [412,413]) have been applied with efficacy to the context of renewable energy acceptance [414–418].

Testing, adapting, and extending the unified theory of domestic hydrogen acceptance would mark a definitive turning point in advancing understanding of the consumer-side of the hydrogen transition [340], as witnessed historically via the evolution of the TAM [88]. As an interim step, subsequent exploration could be carried out by conducting a weight and meta-analysis [102] on the retrieved sample (N = 75) or a larger dataset. A weight and meta-analysis can help validate the causal order of variables [109] for predicting domestic hydrogen acceptance and adoption. Notably, Neves et al. [79] employed this approach to determine the main antecedents of adopting sustainable energy technologies using 44 articles and 48 datasets.

Following the tradition of the UTAUT, this study leverages insights from an integrative, comparative review, grounded in systematic methods, to conceptualise an integrated framework for examining consumer perceptions of domestic hydrogen. To accelerate the promise of net-zero homes, a paradigm shift in energy technology acceptance research is needed, while radical shifts across industry, supply chains, the labour force, and policy making are required in parallel [419]. As the hydrogen economy evolves, this study contends that a true litmus test of social acceptance rests with evaluating socio-psychological, cognitive, and emotional dimensions of human perceptions in parallel. Internalising this notion can help overcome socio-technical barriers [59] to support the evolution of a sustainable hydrogen future.

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3 EXPLORING THE CONTOURS OF CONSUMER HETEROGENEITY: TOWARDS A TYPOLOGY OF DOMESTIC HYDROGEN ACCEPTANCE

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Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Conceptual framework; Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Writing – review & editing, Supervision.

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Highlights

- Hydrogen futures are compromised by a deficit in public awareness and engagement
- Financial risks and equity concerns constrain consumer support for hydrogen homes
- Technology and environmental engagement support domestic hydrogen acceptance
- Consumer heterogeneity will influence the feasibility of deploying hydrogen homes
- Acceptance typologies provide a critical mechanism for energy transitions research

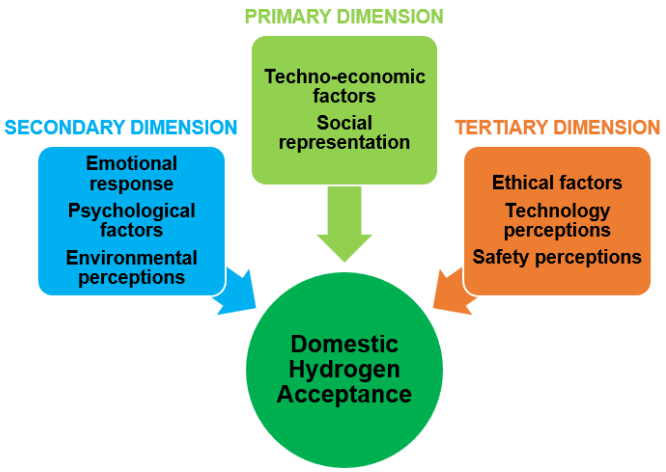
Keywords

Domestic hydrogen; Energy justice; Social acceptance; Technology adoption; Thematic analysis; Typology development

Abstract

Hydrogen energy technologies are anticipated to play a fundamental role in securing a decarbonised energy future. While the deployment of low-carbon hydrogen energy systems remains nascent and is subject to a range of techno-economic constraints, potential scalability will also hinge on social acceptance. Drawing on qualitative responses to an open-ended survey question, the study develops an empirically-grounded typology of domestic acceptance to reflect a multitude of factors influencing consumer attitudes towards low-carbon hydrogen heating and cooking appliances. The typology presents 48 sub-factors of domestic hydrogen acceptance which map to 12 'core factors', representing a mix of positive, neutral, and negative sub-factors, as transmitted by respondents. The study finds that eight primary sub-factors account for close to 60 % of identified codes, with knowledge deficit (negative), environmental benefits (positive), and financial risks (negative) ranking highest. Critically, these three sub-factors are also the most statistically significant predictors of consumer heterogeneity. At the sub-group level, the analysis shows that engagement with renewable energy technology and climate change is associated with stronger perceptions of environmental benefits and lower financial concerns. By contrast, perceived financial risks and concerns over energy injustice constrain acceptance levels among fuel stressed respondents. Through mixed-methods analysis, the study transmits the value of advancing acceptance typologies as a critical mechanism for enacting a 'just' hydrogen economy. The analysis supports developing strategic measures which account for consumer heterogeneity to better support socially acceptable pathways for residential decarbonisation.

Graphical abstract



3.1 Introduction

As climate change pressures continue to mount [1–3], there is an emerging consensus among the scientific community [4,5] and within policy circles [6–8] that hydrogen can play a critical supporting role in the renewable energy transition by 2030 [9]. In the words of Oliveira et al. [10], "a 'hydrogen economy' is an essential secondary energy economy to realising a majority renewable energy society." This prognosis is reflected by the inclusion of low-carbon hydrogen in a wide range of net-zero emissions scenarios [11]. Prospectively, policy and investment decisions taken this decade could spur the growth of a global hydrogen economy towards 2050 [12,13]. Notably, Bridgeland and colleagues [14] argue that hydrogen production is techno-economically viable and can support climate change targets in the United States (US), while enabling more aggressive decarbonisation.

In December 2017, Japan emerged as the first country to release a national hydrogen strategy [15]. In the intervening years, several countries such as Australia [7], Chile [16], and European Union (EU) Member States [17] have followed in Japan's footsteps by developing official strategies (see Appendix M). Of foremost relevance to this study, the United Kingdom (UK) government published its hydrogen strategy in August 2021 [18] ahead of COP26 in Glasgow [19]. Notably, the strategy sets out a vision for enabling production, distribution, storage, and use of hydrogen to support economic opportunities across the country's industrial heartlands [18].

The UK government foresees a potential role for hydrogen in residential decarbonisation [18], alongside heat pumps, district heating [20,21], and other electric-based technologies such as induction hobs [22,23]. Importantly, prospects for 'hydrogen homes' – combining low-carbon hydrogen boilers and hobs [24,25] – entail a definitive spatial component [26,27] which may present synergies with industrial decarbonisation via hydrogen [28]. Reflecting these spatial dynamics, the government's strategy envisions the launch of hydrogen village trials [29–31] in proximity to industrial clusters [32–34], ahead of a strategic decision on the role of domestic hydrogen in 2026 [18].

A prominent example of recent hydrogen research, development, and deployment activities is the HyDeploy project, which Isaac [35] describes as "the first stepping-stone for setting technical, operation and regulatory precedents of the hydrogen

vector."[1] The third and final phase of the project (HyDeploy3) focuses on enabling government policy on domestic hydrogen [36]. Supporting related social science research on domestic hydrogen acceptance [37–40], part of the HyDeploy evidence base includes a comparative assessment of consumer perceptions of blended hydrogen in Keele (West Midlands) and Winlaton (Northeast England) [41].

As summarised in the literature [26], other projects such as H21 (Leeds) [39,42], Hy4Heat (Tyne and Wear) [43] and H100 (Fife) [30,44,45] have seen the UK emerge as a frontrunner in exploring the feasibility of hydrogen pipelines and domestic appliances [46–49], which are emergent topics in the technical literature [50–56]. While the UK has assumed a leadership role in these areas of the hydrogen economy, parallel activities are underway in several countries such as Australia [57–59], Japan [60,61], Canada [62–64], the Netherlands [65,66], Germany [67–69], France [70], and Italy [71].

Although techno-economic barriers to deploying and scaling up hydrogen energy systems remain at the fore, at least in the short-term [49], establishing social acceptance for hydrogen energy technologies and associated infrastructure (e.g. carbon capture and storage) will prove paramount to enabling large-scale technology diffusion [72,73]. Notably, Sharma et al. [74] categorise social acceptance as a 'motor theme' of transitioning to a hydrogen economy, as opposed to a 'basic', 'niche', or 'emerging or decline' theme. Furthermore, Almaraz et al. [75] argue that "public participation is needed to guarantee a fair and transparent evaluation of hydrogen vs other fuels." However, to date, social science research on the hydrogen economy remains relatively scarce [9,75], with most studies limited to the context of fuel cell vehicles and fuelling stations [73,76], while domestic hydrogen acceptance is a more nascent topic [37,77].

Against this backdrop, this study has three connected aims: (1) to identify the salient core factors of domestic hydrogen acceptance in view of the expressed attitudes and reflections of survey respondents; (2) to determine the salient sub-factors of domestic hydrogen acceptance based on this evidence base; and (3), to establish which sub-

[1] The first phase of the project (HyDeploy1) took place in Staffordshire between 2017 and 2019, where hydrogen was blended into Keele University's private gas grid. The second phase of the project (HyDeploy2: August 2021 and June 2020) involved supplying several hundred houses and other buildings in Winlaton, Northeast England, with a 20% hydrogen blend.

factors predict consumer heterogeneity. Pursuing the final line of inquiry is crucial since Bharadwaj and colleagues [78] have shown that the effects of information provision on different consumer sub-groups are heterogeneous, while divergent consumer preferences for cooking and heating technologies have been reported in the UK context [23]. Moreover, subsequent research demonstrates heterogeneous preferences for living in a hydrogen home among different parts of the UK housing stock [79]. Through conceptual and empirical contributions, the main objective of the research is to advance an initial typology of domestic hydrogen acceptance, which can be refined or extended in subsequent research to support public engagement in the domestic hydrogen transition, while accounting for the influence of consumer heterogeneity.

To achieve its stated objective, this study draws on written responses (N = 1064) to an open-ended question which closed the online survey, wherein participants communicated a wide range of attitudes reflecting different acceptance factors. Specifically, several iterations of hybrid deductive-inductive coding were performed to derive the final set of acceptance sub-factors (N = 48), which map to 12 core factors (see Section 3.4).

Contributing to the growing evidence base on energy acceptance, the proposed typology demarcates critical parameters for supporting a socially acceptable transition to hydrogen homes and the wider hydrogen economy. This marks a novel contribution to the ‘hydrogen futures’ literature [49,80], as the first study to derive an acceptance typology based on qualitative evidence sourced from a dataset of over 1000 individual responses. By contrast, previous studies have largely relied on secondary data from literature review to identify the salient factors of hydrogen acceptance [76,81].

The remainder of the paper is structured as follows. Section 3.2 reviews the literature on hydrogen acceptance, while Section 3.3 reports the research design and mixed-methods approach. Next, Section 3.4 reports the results which includes analysing the predictors of consumer heterogeneity in Section 3.4.6. The key findings are discussed in Section 3.5, while Section 3.6 concludes the study by proposing policy recommendations and outlining a future research agenda.

3.2 Literature review

3.2.1 Conceptualising domestic hydrogen acceptance

Reflecting on the configuration of past, ongoing, and emerging national energy transitions [82–85], social acceptance [86–88] – understood as a complex, multi-actor and cross-scalar phenomenon [89–91] where the 'positions' of respective actors are dynamic and continuously evolving [92] – constitutes a precondition for the rapid diffusion of low-carbon energy technologies [90,93,94]. Historically, social acceptance scholarship has focused on socio-political, market, and community acceptance dimensions [95] to reflect people's response to renewable energy technologies [88]. However, in the context of domestic energy adoption [96], it is imperative to include a direct research focus on attitudinal and behavioural acceptance to better understand consumer perceptions, attitudes, motivations, and preferences [26,97–99].

3.2.2 Insights from systematic literature review and narrative literature review

Despite the recognised imperative to move beyond a predominantly techno-economic focus on the hydrogen transition [100], a comprehensive bibliometric analysis conducted by Kar et al. [9] highlights a pronounced deficit in social science research on the hydrogen economy. Although Kar et al. [9] reviewed 1275 articles on the hydrogen economy, a paucity of research beyond technical areas was strongly reflected by their analysis of keywords, among other metrics such as citation count (see Appendix M).

Emodi et al. [76] conducted a systematic literature review (N = 43) on hydrogen acceptance studies published between 2008 and 2020, which provides a critical starting point for understanding contributions to date. At the outset it should be highlighted that only five studies in the sample entailed a focus on domestic hydrogen appliances. The review demarcated seven 'determining factor categories' of hydrogen acceptance consisting of aspects such as ***environmental awareness***, ***psychological needs***, and ***economic beliefs***. In total, 30 sub-factors were identified in the review, although this number reduces to 20 when excluding demographic factors. However, it should be noted that *prior knowledge of hydrogen* was included in the list of demographic factors, occurring in 14 of the studies (see Table M-1).

Subsequently, Scovell [87] reviewed 27 quantitative studies on hydrogen acceptance covering the period 2005–2021 (see (see Table M-1), which also reflected a primary focus on hydrogen fuel cell vehicles (HFCVs) and hydrogen fuelling stations (HFSs). The results further demonstrate the potential for differentiating between different aspects of hydrogen acceptance, following the identification of 13 specific factors [87] which in several cases correspond closely to the categorisation presented by Emodi et al. [76].[2]

To overcome the sampling limitations of Emodi et al. [76] and Scovell [87], Gordon et al. [77] reviewed 17 studies engaging with domestic hydrogen acceptance between 2017 and 2022.[3] Whereas prior reviews [73,76] developed factor categories based on frequency of occurrence across the sample, Gordon et al. [77] qualitatively assessed the evidence base on domestic hydrogen acceptance. In doing so, the authors [77] identified 14 factors which were demarcated according to a specific ranking classification composed of five positions: critical (2), major (4), significant (3), moderate (4), and minor (1).

The 14 factors broadly align with previous demarcations,[4] in addition to identifying a set of context-specific factors, such as ***consumer disengagement in energy markets***, ***the lived experience of heating and cooking***, and ***technology choice*** [77] (see Table M-1). Nevertheless, at the methodological level, the results on domestic hydrogen acceptance presented by Gordon et al. [77] are subject to the same limitation of Scovell [87] in terms of sample size, which reflects the constraints of a narrative literature review in contrast to a systematic review [101].

Most recently, Almaraz et al. [75] conducted a systematic literature review (N = 65) focused on hydrogen research engaging with social aspects. The authors [75] identified twelve categories composed of over 40 sub-factors, with which this study directly engages (see Section 3.5). Notably, ***information*** featured as a top-ranking

[2] For example, Scovell [87] identified ***social trust*** as an acceptance factor, alongside ***awareness***, ***subjective knowledge***, and ***objective knowledge***, in addition to ***perceived risk/safety concerns***, and ***perceived benefit/value/usefulness***, among other factors.

[3] However, seven studies focused on a range of hydrogen technologies, as opposed to solely the residential context, as evidenced by studies engaging with the Australian hydrogen economy [195,284–286]. Moreover, only six studies were sourced from the academic literature [25,37,193,276,280,287], which underscores the need for wider scholarly engagement, particularly beyond the UK [25,37], European [193,280,287], and Australian context [276].

[4] For example, financial costs, knowledge and awareness, environmental impacts, public trust, affective response, economic impacts, distributional injustice, and procedural injustice [77].

category composed of several sub-factors: *awareness of carbon footprint*, *awareness of hydrogen*, *communication*, *discourse*, *spreading of information*, *knowledge*, and *education* [75]. However, ***social acceptability***[5] was identified as its own category (ranking 4th) as opposed to the outcome variable or target factor [75]; reflecting the broader focus on the hydrogen economy, as opposed to social acceptance of a specific technology application or range of technologies.

3.2.3 Insights from focus groups studies and online surveys

In parallel to the review studies summarised in Section 3.2.2 [73,75–77], primary data collection on hydrogen acceptance has steadily increased. For example, a series of quantitative studies have been conducted on consumer attitudes towards HFCVs in India [102–105], alongside qualitatively-driven analyses on domestic hydrogen in the UK context [23,106,107].

Through mixed-methods data analysis (i.e. qualitative data and poll data), prior research [23,106,107] has analysed a wide range of factors identified in the literature (see Table M-1). Results suggest existing gas users are somewhat open to the idea of adopting hydrogen appliances, but have divergent views towards boilers and hobs [23], which is in line with the finding of Scott and Powells [25]. Additionally, respondents expressed stronger support for 'green' (renewable-based) hydrogen compared to 'blue' hydrogen production (i.e. reliant on natural gas and carbon capture and storage) [107], which aligns to international findings [108–110].

Additionally, research in the Australian context has been advanced by Dumbrell et al. [111], Lozano et al. [76] and Bharadwaj et al. [78], as summarised in Table M-1. Notably, Bharadwaj and colleagues [78] found that respondents' general support for hydrogen depends on their socio-economic characteristics and geographic location, thereby highlighting the importance of consumer heterogeneity. Furthermore, Scovell and Walton [81] conducted in-person focus groups to explore public perceptions of hydrogen energy technologies across the supply chain. However, following a procedure of reflexive thematic analysis, the authors [81] failed to evaluate eight identified acceptance categories in terms of importance. Therefore, it remained challenging within the context of the qualitative analysis to directly estimate whether,

[5] In 1982, Otway and Von Winterfeldt explained that "the social acceptability of large-scale technologies depends upon a wide range of things, some related to safety and economics, but also some factors of cultural, social, and psychological significance" [288].

for example, risk factors or perceived benefits are more prevalent in the mind of Australians [81]. Relatedly, in some cases, it was somewhat unspecified whether identified factors have a positive, negative, or neutral influence on hydrogen acceptance [81].

Across the reviewed studies, researchers have applied different terminologies to capture hydrogen acceptance factors and, in several cases, sub-factors. While the growing evidence base has enriched knowledge on hydrogen acceptance, it must be emphasised that the subjective nature of inductive coding may at times give rise to potential miscategorisation, or otherwise reflect instances of strong overlap between identified categories (see Table 3-1). This observation highlights the need for carefully defining acceptance categories and sub-factors, while delineating the wider research context, which is closely adhered to in this study (see Section 3.3.5).

Table 3-1. Limitations of coding techniques in the hydrogen acceptance literature.

Study	Description of coding procedure(s) applied	Limitations of the coding technique
[76]	• Categorises *distributive benefits* under ***economic benefits***[a] • Assigns *social equity* to ***social influence***	• These sub-factors were assigned to different categories despite sharing a general link to one of three tenets of energy justice [112–114], namely, distributional justice [115,116]
	• *Prior knowledge* was assigned to ***demographic factors***	• However, *environmental knowledge* was assigned to ***environmental awareness***, while the ***psychological needs*** category is unused for sub-factors related to knowledge
[81]	• Presents ***safety and risk perceptions*** as a mixed category	• The category also includes perspectives regarding hydrogen as less risky for people's health compared to conventional fuels, in view of its environmental benefits
	• ***Frames environmental impacts*** exclusively in terms of perceived benefits • ***Water use*** refers to negative impacts related to scarcity issues	• This separation, while justifiable to an extent, raises the question as to whether it would be more logical to subsume both benefits and risks under the same category, while making use of sub-themes or sub-factors as performed by Emodi et al. [76]
	• Frames ***hydrogen competing with other renewables*** exclusively as a risk factor that may delay the low-carbon transition	• Respective hydrogen production pathways may compete with or compliment the deployment of renewables, as evidenced by the UK's twin-track strategy [18,107] and highlighted in a recent case study [49]
[75]	• Demarcates ***socio-political factors*** in relation to *energy security* (N = 10), *equality* (N	• Appears to conflate sub-factors belonging to the economic domain and social

	= 2), *energy justice* (N= 4), *well-being* (N = 6), and other *socio-political factors* (N = 9)	fairness, while assigning an unspecified generalised category (i.e. other)
•	***Acceptability*** is reflected with an identical sub-factor (*acceptability*, N = 26), while 7 other sub-factors (N = 41) complete the category, with *trust* having the lowest frequency (N = 1)	• The application of a self-reflecting sub-factor, as also applied in the socio-political category, compromises the ability to distinguish between factors that compose the acceptability theme, and thereby partially contaminates the data analysis
•	***Socio-economic factors*** is composed mainly of *other socio-economic factors* (N = 15), in addition to jobs and labour (N = 6)	• The authors give no explanation of what aspects compose the 'other' category and fail to justify why this approach is taken, whereby the 'other' assignment comprises most of the category
•	***Research and development*** (N = 19) and ***Technological safety*** (N = 14) have no sub-factors	• Both factor categories are composed of their main factors exclusively, which is inconsistent with the approach applied elsewhere in the analysis wherein sub-factors compose each category

[a] Throughout this study, core factors of hydrogen acceptance are denoted in ***bold italics***, while sub-factors are denoted in *italics*.

3.2.4 Summary of literature review findings

Based on the literature review results, there are three key limitations constraining knowledge on hydrogen acceptance, which this study aims to address. Firstly, research focusing on the residential context is a more recent development [77] and therefore less represented in the literature [76], which this study helps directly address through its stated focus. Secondly, it emerges that previous studies have sometimes conflated or miscategorised acceptance factors leading to a lack of coherence within and between studies, which can be counteracted through a more rigorous approach, as applied in this study (see Section 3.3). Thirdly, emphasising the importance of consumer heterogeneity is a recent research advancement [23], which may reflect higher levels of support for hydrogen as technology engagement, environmental awareness, and (hydrogen) knowledge levels increase [78,109]. As demonstrated in Section 3.4.6, exploring the potential for group-specific differences in relation to consumer perceptions represents a focal point of this analysis, which significantly advances the discourse on domestic hydrogen acceptance.

3.3 Material and methods

This section describes the methodology in five stages, which includes firstly reporting the techniques for developing the online survey in Section 3.3.1 and the multigroup

research design in Section 3.3.2. Next, Section 3.3.3 provides an overview of the mixed-methods approach to data analysis, while Section 3.3.4 outlines details regarding the use of typologies as an analytical tool. Subsequently, Section 3.3.5 describes the coding procedures and research step. Finally, Section 3.3.6 reports the statistical procedures carried out to support the multigroup analysis through a comparative assessment of consumer heterogeneity.

3.3.1 Online survey development

Between October and December 2022, the research team conducted an online survey to examine public perceptions of domestic hydrogen in the UK context. The survey design was informed by findings from literature review (see Section 3.2) and results from online focus groups carried out in Spring of 2022 [23,106,107]. Accordingly, the survey instruments were informed by qualitative insights [117], which guided the identification of relevant acceptance factors [81,118].

Qualtrics software [119] was used to program the survey, which was validated through pilot tests, in addition to feedback rounds from hydrogen experts and social scientists. The survey took approximately 15 to 20 minutes to complete and engaged respondents with several aspects of domestic hydrogen acceptance, as reflected by 15 distinct question categories,[6] which included psychological, technological, financial, economic, environmental, safety, and behavioural aspects of domestic hydrogen acceptance, among other factors. All survey items were measured using either a five-point or eleven-point Likert scale.

Acknowledging the content of the online survey at the outset is vital, since most of the identified factors composing the acceptance typology were reflected within the survey question items. To facilitate engagement and more meaningful responses, the survey also included information provision on hydrogen production methods, hydrogen developments in the UK, and hydrogen home appliances (i.e. boilers and hobs) [120].

[6] (1) Knowledge and awareness of hydrogen and low-carbon technologies; (2) hydrogen production pathways vis-à-vis the UK's twin-track strategy; (3) perceptions of appliance performance (i.e. hydrogen boilers and hobs); (4) financial perceptions (i.e. purchasing and running costs of domestic hydrogen); (5) hydrogen safety perceptions; (6) perceived socio-economic costs; (7) perceived risks (i.e. disruptive impacts); (8) perceived community benefits; (9) facilitating conditions (i.e. perceived likelihood of local deployment); (10) stakeholder trust; (11) attitudinal preferences; (12) emotional response; (13) behavioural acceptance (i.e. willingness to adopt domestic hydrogen); (14) social acceptance; and finally, (15) willingness to pay for the domestic hydrogen transition.

The data analysed in this study is drawn from qualitative responses to an open-ended instruction which concluded the survey (N = 1845). The request for written reflections was formulated as follows:

***Please use this text box to explain more about your attitudes towards hydrogen or any other reflections on this topic*.**

In total, around two-thirds of respondents provided a written statement (N = 1213), which were initially analysed to derive consumer positions (i.e. hydrogen optimist, hydrogen hopeful, hydrogen curious, hydrogen neutral, hydrogen cautious, hydrogen sceptical, and hydrogen pessimist) composing a proposed 'hydrogen acceptance matrix' [121]. As a result, the dataset analysed within this study draws on 88% of responses (N = 1064), as described in Section 3.3.5. As opposed to prior research which has identified acceptance factors through literature review [75–77], this study is distinct in deriving an empirically-grounded typology based on primary qualitative data. It follows that the acceptance factors identified within this analysis are derived from respondents' own attitudes and reflections towards the domestic hydrogen transition, which has potential implications for observed response patterns (see Section 3.6).

3.3.2 Multigroup research design

As reported in Table 3-2, this study is grounded in a multigroup research design, comprised of four specific consumer segments, which taken together provide a rich qualitative evidence base for mixed-methods analysis. The underlying rationale for adopting this approach was to facilitate opportunities for comparative analysis between consumers with different levels of technology and environmental engagement (i.e. awareness, knowledge, or interest), while also accounting for the potential influence of fuel stress on domestic hydrogen acceptance.

International research has shown that technology and environmental engagement predict consumer acceptance for smart home technologies [122–124], battery electric vehicles [125,126], solar PV [127–131], and residential micro-generation technologies [132] including energy-efficient heating appliances [133]. While these findings appear to hold equally true for hydrogen energy technology acceptance [107,109,134], this study is motivated by the need to consolidate earlier inferences where research methods lacked theoretical rigour [135] or were otherwise constrained by small sample sizes [73].

Table 3-2. Consumer sub-groups composing the survey sample.

Sub-group	Total sub-sample size (%)	Sub-sample size for this study (%)	Consumer specifications
Moderately Engaged Group (MEG)	N = 458 (24.8)	N = 275 (25.8)	• Moderate level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Moderate interest and engagement in environmental issues • Not experiencing fuel stress
Very Engaged Group (VEG)	N = 331 (17.9)	N = 206 (19.4)	• High level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Strong interest and engagement in environmental issues • Not experiencing fuel stress
Fuel Stressed Group (FSG)	N = 379 (20.5)	N = 212 (19.9)	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Living in fuel poverty or experiencing high levels of fuel stress
Baseline Group (BLG)	N = 677 (36.7)	N = 371 (34.9)	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Not experiencing fuel stress
Total	1845	1064 (57.7)	

To support the multigroup approach, quotas were implemented to help approximate a nationally representative survey sample, which was secured in terms of location and gender, and partially achieved in respect to age, housing tenure, and housing type. Additionally, socio-demographic information was recorded such as educational level, annual income, and number of occupants per household. As a result, each consumer sub-group proved broadly nationally representative of the UK population in regard to key socio-structural variables [77], while distinguishable in terms of technology and environmental engagement levels (see Fig. 3-1),. Additionally, the inclusion of a fuel

stressed group (FSG) served as a reliable proxy to account for the influence economic factors (i.e. without the need to set a specific quota for annual income).

Following a series of filtering questions (see Fig. 3-1), the final sample was composed of homeowners (outright or mortgage) currently using natural gas appliances (both for heating and cooking), with an at least moderate level of involvement in purchasing these appliances. Finally, respondents perceived their ability to choose between technologies to be at least somewhat important. Through this approach, the analysis engages with consumers that are most likely to be involved in and impacted by prospective decarbonisation of the UK gas grid.

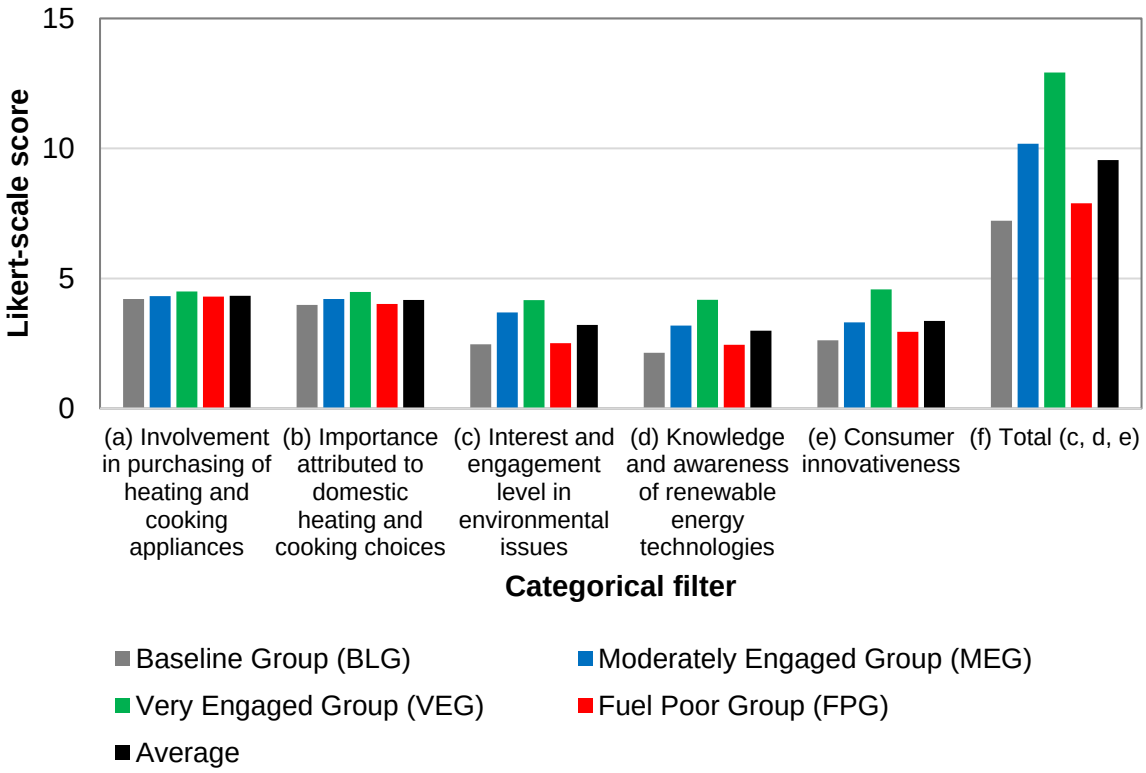


Fig. 3-1. Responses to filtering questions across consumer sub-groups (N = 1064).

3.3.3 Mixed-methods data analysis

To derive statistical inferences from participant statements, this analysis is grounded in an integrated mixed-methods approach [136], whereby qualitative and quantitative contributions are captured within the same study [137,138] to support deeper insights and stronger explanatory power [136].

Qualitative research approaches – relying on textual and other forms of non-numerical data [136,139] – are better suited to generating theories about underexplored

phenomena [138], such as renewable energy acceptance [95,140] and emerging low-carbon technologies [26,89,118,141]. By contrast, quantitative research "adopts structured procedures and formal instruments for data collection" [142]. Quantitative analysis adheres to objective and systematic methods which operationalise a given set of variables [142] to measure magnitude and frequency, explore relationships between sub-groups, and test theories [138].

Mixed-methods research should focus strongly on the 'conversation' that develops when qualitative and quantitative research components interact with one another [138]. By establishing a dialogue between both strands [143], mixed-methods analysis seeks to enable "a seamless transfer of evidence across qualitative and quantitative modalities," thereby integrating insights from explanatory descriptions and statistical analyses [136]. Notably, through "understanding the underlying dynamics and meaning-making associated with constructs" [144], qualitative data can provide insights on a given problem that cannot be directly quantified [142].

Through a mixed-methods approach drawing on over 1000 responses from the UK public, this study addresses the methodological limitations of previous studies, which can be characterised as follows: (1) lacking primary data due to a reliance on data sourced from literature review [73,75–77]; (2) conducting focus groups analyses constrained by small-sample sizes and an exploratory lens [23,106,107]; and (3), quantitative assessments which can only partially reflect consumer positions and expressions [78,109,111].

3.3.4 Typology development

As discussed by Collier et al. [145] in the context of political science, typologies have been increasingly leveraged as analytical tools across a range of research domains; featuring prominently in fields of psychology and sociology [146], alongside growing research areas such as socio-technical transitions [147,148]. While Collier et al. [145] outlined twelve guidelines for working with typologies, Kanger [148] recently provided seven recommendations to advance typology-building for energy transitions research; drawing insights from conceptual typologies focused on intermediaries [149], energy justice [150], and power dynamics[151].

A typology is developed hierarchically [145,152] by grouping empirical data into specific categories according to similarities, and indirectly, by way of shared

differences [146]. Accordingly, typology development provides a means to examine the homogeneity within and the heterogeneity between sub-groups, so that statistical conclusions can be drawn [143,146]. Success is achieved when one data type (e.g. qualitative statements or literature review findings) produces a specific typology that anchors the analysis within an underlying framework [143].

Critically, typologies can bridge the limitations of quantitative and qualitative research by elucidating the dimensions of an underlying concept [145], such as domestic hydrogen acceptance [26]. Furthermore, typologies can provide a conceptual foundation for subsequent statistical analysis [153], while enabling the researcher to focus on specific variables of interest, in addition to supporting a more comprehensive synthesis of evidence and conclusions [145]. As noted by Kanger [148], typologies can help organise existing knowledge and direct empirical analysis.

The application of typologies to energy case studies is well documented in the literature [148]. For example, through literature review, Darmani et al. [154] formulated a comprehensive typology to assess drivers of renewable energy technologies (RETs), whereas Kerr et al. [155] employed case study analysis to propose an explanatory typology of community benefits from renewable energy development. More recently, Raška et al. [156] utilised case studies grounded in mixed-methods data to advance a theory-driven typology of planning decisions associated with land use conflicts. Additionally, Frantál et al. [157] combined interview data and statistical analysis to develop an empirically-grounded typology of wind energy conflicts. Other researchers have adopted similar systematic techniques to examine clean energy communities [158], eco-innovation and green growth [159], and energy security [160].

Typologies have also guided research developments across critical areas of the water, energy, and food nexus [161], including barriers to delivering sustainable urban water management [162] and developing multi-stakeholder platforms for integrated water resource management [163]. In the Belgian context, Serbruyns and Luyssaert [164] interviewed private forest owners to develop a typology for supporting management practices in relation to policy preferences. More recently, Tanguay et al. [165]. drew on 65 case studies across 15 countries to examine factors influencing the social acceptance of biodiversity and habitat conservation measures on private land.

The contribution of Tanguay et al. [165] is notable to this study for two reasons: (1) demonstrating the efficacy of a two-layer typology composed of six main categories and 45 subcategories, which correspond to positive and negative, as well as neutral or mixed factors of social acceptance; and (2) highlighting the requirement of available studies for developing an acceptance typology through systematic literature review, which is constrained by the paucity of studies on domestic hydrogen acceptance [77].

3.3.5 Coding procedures

The methodology reflects the application of hybrid deductive-inductive coding to thematic analysis [166,167], in line with established methods in the social sciences [168,169]. While inductive analysis proceeds without a predetermined theory or framework, the deductive approach rests on processing data in relation to pre-established concepts and themes [170,171], which is guided in this study via the selected survey questions (see Section 3.3.1). In addition to drawing on a deductive *a priori* template of codes [172] for hydrogen acceptance factors [77,135], the open-ended nature of the final survey question facilitated a data-driven inductive approach [173], whereby salient factors could emerge from within the data [167,174] and be cross-compared to assess validity [175,176].

In sum, the coding procedure involved five distinct steps which are outlined in Fig. 3-2 and demonstrated in Section 3.4.1. Firstly, an acceptance typology was developed from the full dataset of responses (N = 1213), before applying a stricter inclusion criteria. In total, around 88% of responses (N = 1064) made explicit reference to at least one specific hydrogen acceptance factor, thereby qualifying for further analysis. The analysis adhered to ensuring the identified categories (i.e. core factors and sub-factors) had minimal overlapping components, while reflecting broad coverage of phenomenon of interest [148].

Critically, the excluded responses (N = 149) relayed more general reflections towards domestic hydrogen [121], without citing a specific factor, or communicating an explicit positive or negative emotion. For example, around two-thirds of excluded statements corresponded to neutral or agnostic perceptions of hydrogen (N = 101). Accordingly, these responses were discarded to support a clear and systematic acceptance typology [148], but incorporated in parallel research to reflect a ‘hydrogen neutral’ position [121].

The least cited sub-factor was *town gas experience* (N = 1) – categorised to the 'core' factor, ***image*** – as communicated within the following response:

> "*The energy companies that run the distribution networks and British Gas make enough profits to pay for it. You will still be using the same distribution network pipeline. You won't have to change that. It will just be like when we went from coal gas to natural gas. Most of the old pipeline has been renewed now*" (MEG 254).

Other infrequently mentioned sub-factors included energy security risks (N = 3) and age barrier (N = 3), which are defined in Appendix M (see Table M-2), alongside all identified sub-factors (48 in total).

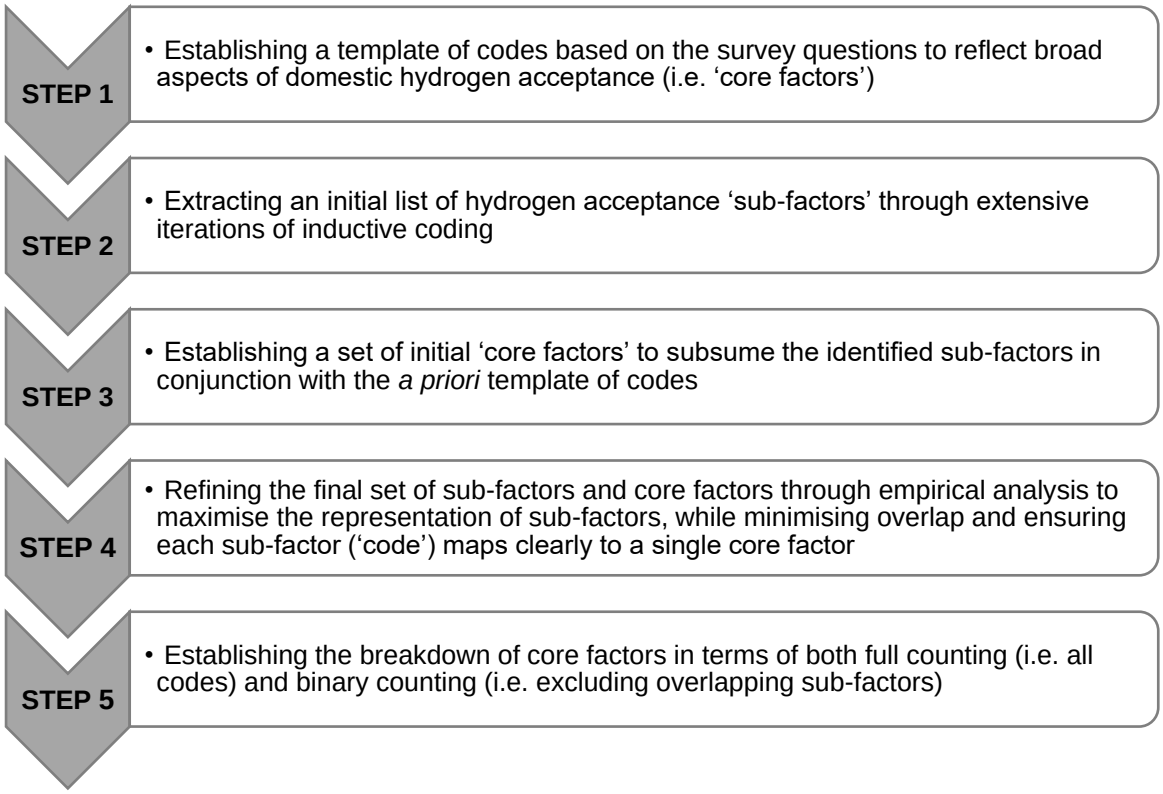


Fig. 3-2. Coding procedures and research steps.

3.3.6 Quantitative analysis of consumer heterogeneity

Categorising and quantifying participant statements marks an iterative process [177,178] of data transformation [117,138,179]; adhering to definitive and transparent steps which can be replicated [180] to promote dialogue between research groups [181]. In terms of quantitative methods, various descriptive statistics were analysed to support the analysis of *sub-factors* of domestic hydrogen acceptance (primary, secondary, and tertiary), which represent a group of ***core factors***.

Thus, the main interest lies in detecting the frequency and scope of response patterns (positive, neutral, and negative) and organising these trends into a robust acceptance typology, which extends from the core level (12 factors) to the sub-level (48 factors). The assessment of group differences is supported by evaluating the relative frequency of response types (i.e. *sub-factors*) across consumer sub-groups, thereby controlling for differences in sample size.

Consumer heterogeneity is further examined through a series of non-parametric tests (Kruskal-Wallis H Test) and post-hoc tests, which are performed in IMB SPSS (version 28.0). Two post-hoc tests are applied in Section 3.4.6 to report the adjusted *ρ*-value (Bonferroni correction) and effect size (*r*). SPSS outputs provide the adjusted *ρ*-value, which is calculated by dividing the original *ρ*-value by the number of analyses on the dependent variable [182]. *r* is calculated using the following formula, where *Z* = standardised value for the test statistic; and n = sample size [183]:

$$r = \frac{Z}{\sqrt{n}}$$

The following cut-offs are applied to evaluate effect size: small: 0.01 – < 0.08; moderate: 0.08 – < 0.26; large: > 0.26 [184,185].

Overall, the analytical process adopted in this study involves three main stages: (1) coding the qualitative dataset to establish hydrogen acceptance factors; (2) descriptively and statistically examining the transformed dataset; and (3), synthesising the findings through a coherent narrative which weaves together both strands of evidence [136]. Through these steps, a systematic and rigorous method is implemented to construct a typology of domestic hydrogen acceptance based on extensive qualitative data (see Fig. 3-3).

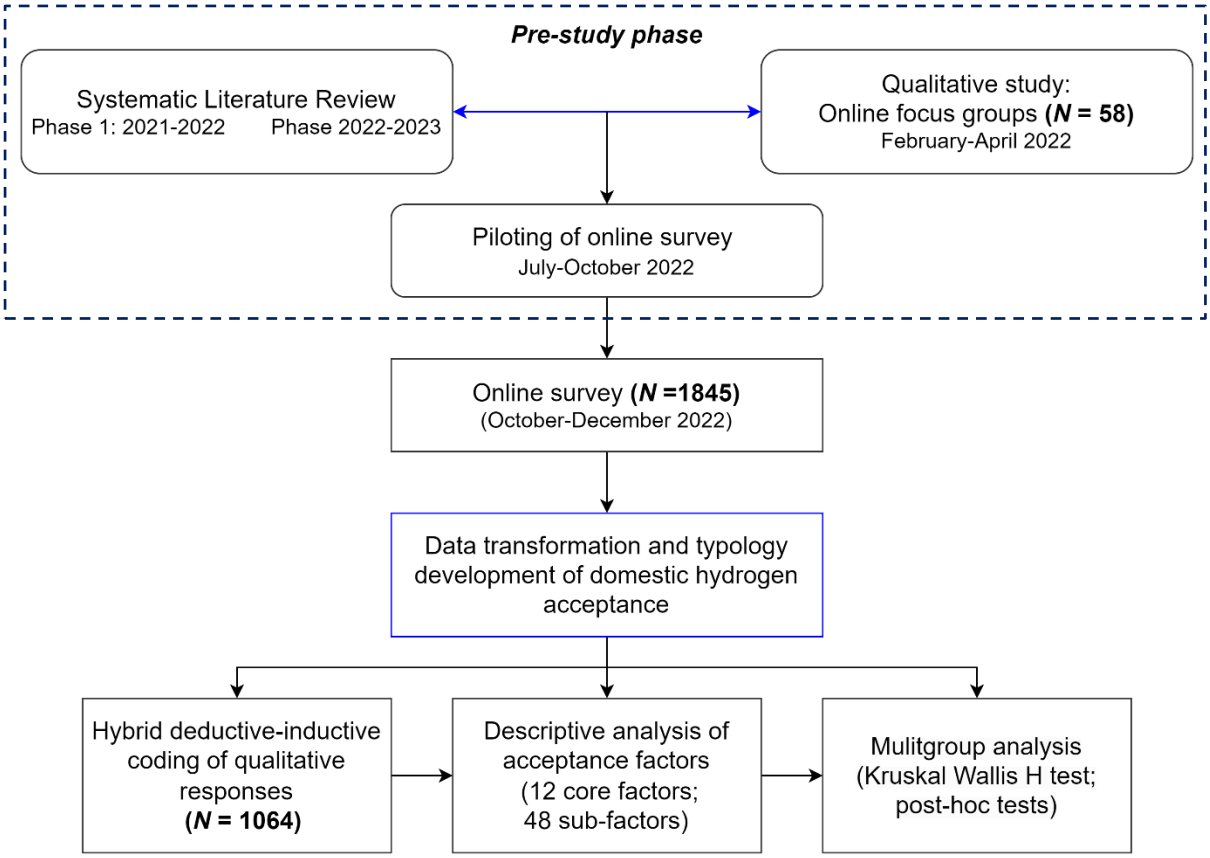


Fig. 3-3. Mixed-methods research design.

3.4 Results

The results are reported by way of six sub-sections beginning with a breakdown of core factors and sub-factors of domestic hydrogen acceptance in Section 3.4.1 and Section 3.4.2. Next, Section 3.4.3 reports the analysis of primary sub-factors, while Section 3.4.4 and Section 3.4.5 analyse secondary and tertiary sub-factors of domestic hydrogen acceptance. Lastly, Section 3.4.6 identifies and discusses sub-factors (primary and secondary) which are statistically significant predictors of consumer heterogeneity.

3.4.1 Core factors of domestic hydrogen acceptance

3.4.1.1 Results from full counting

In total, 2180 references to specific perceptions of domestic hydrogen were detected across the sample (*M* = 2.05 per respondent; *SD* = 1.16). Overall, the number of references to hydrogen acceptance factors per sub-group deviated only marginally from the sample distribution, which indicates each group was close to equally engaged in the topic. Following the procedure described in Section 3.3.4, this analysis identifies

12 categories or ‘core factors’ reflecting consumer attitudes towards domestic hydrogen, which are defined in Table 3-3. Firstly, the results are evaluated without accounting for areas of overlap within responses at the factor level (i.e. full counting), which enables the composition of each core factor to be clearly demarcated. Secondly, areas of overlap are calculated, and factors are discounted (i.e. binary counting) to support a more accurate breakdown of core factors, which provides a basis for comparative assessment in Section 3.5.

Three core factors had a predominantly positive composition, foremost, ***image***, followed by ***environment*** and ***performance***, while two were positively skewed, namely, ***social*** and ***economy***. By contrast, ***fairness and equity*** and ***logistics*** are composed of exclusively negative responses, while ***finance*** and ***safety*** were negatively skewed. The remaining factors – ***affect***, ***information***, and ***technology*** – were largely neutral, with the former proving particularly balanced in terms of positive and negative emotions. Accordingly, Table 3-3 defines each core factor and reports its respective composition and classification based on the results from full counting.

Table 3-3. Summary of core factors influencing domestic hydrogen acceptance.

Factor	Definition of core acceptance factor	Positive (%)	Neutral (%)	Negative (%)	Total (%)	Classification
Information	• Knowledge, awareness, and perceptions of hydrogen, and attitudes towards research and communication practices regarding domestic hydrogen	7.6	0.0	10.1	17.7	Primary
Image	• Conceptual perception of hydrogen fuel and hydrogen technologies	12.2	0.0	1.2	13.3	Primary
Finance	• Perceptions of financial costs associated with hydrogen homes	0.9	4.1	7.7	12.7	Primary
Affect	• Expressed emotions and feelings regarding hydrogen fuel and activities associated with the domestic hydrogen transition	6.7	0.0	6.0	12.6	Primary
Environment	• Environmental perceptions of hydrogen homes and underlying attitudes towards climate change and the environment	8.4	1.7	0.6	10.8	Primary
Fairness and trust	• Perceived fairness regarding the decision-making processes of deploying hydrogen homes (i.e. procedural and recognition justice, trust and choice), and the distribution of benefits, costs, and risks (i.e. distributional justice)	0.0	0.0	10.1	10.1	Primary
Technology	• Attitude towards energy technologies and technological change	2.8	0.0	2.2	5.0	Secondary
Safety	• Safety perceptions of hydrogen homes	0.6	1.2	2.9	4.8	Secondary
Economy	• Macro-economic perceptions of hydrogen homes and attitudes towards the UK economy	2.9	1.3	0.5	4.7	Secondary
Logistics	• Perceptions of logistical and practical drivers or barriers associated with the transition to hydrogen homes	0.0	0.0	3.7	3.7	Secondary
Social	• Perceptions of societal and community impacts	1.6	0.4	0.5	2.5	Secondary
Performance	• Perceptions of hydrogen's potential impact on the efficiency or utility of heating and cooking appliances	1.6	0.0	0.4	2.0	Secondary
		45.4	**8.7**	**45.9**	**100.0**	

Source: Author's compilation with definitions adapted from [73,135,186,187].

The identified core factors were further classified according to a weighting system for clearer demarcation. Half of the group qualified as 'primary' factors, wherein each factor represented more than 10% of coding results. Primary core factors accounted for 77% of responses, whereas the remaining 23% were classified as 'secondary' factors (<10% of codes). Among the primary group, ***information*** ranked highest (17.7%), followed by ***image*** (13.3%), ***finance*** (12.7%), ***affect*** (12.7%), ***environment*** (10.8%), and ***fairness and equity*** (10.1%). Among the secondary group, ***technology*** (5.0%), was closely followed by ***safety*** (4.8%), ***economy*** (4.7%), ***logistics*** (3.7%), ***social*** (2.5%), and ***performance*** (2.0%). The results are visualised in Fig. 3-4 and further illustrated in Fig. 3-5 based on the data reported in Table 3-3.[1]

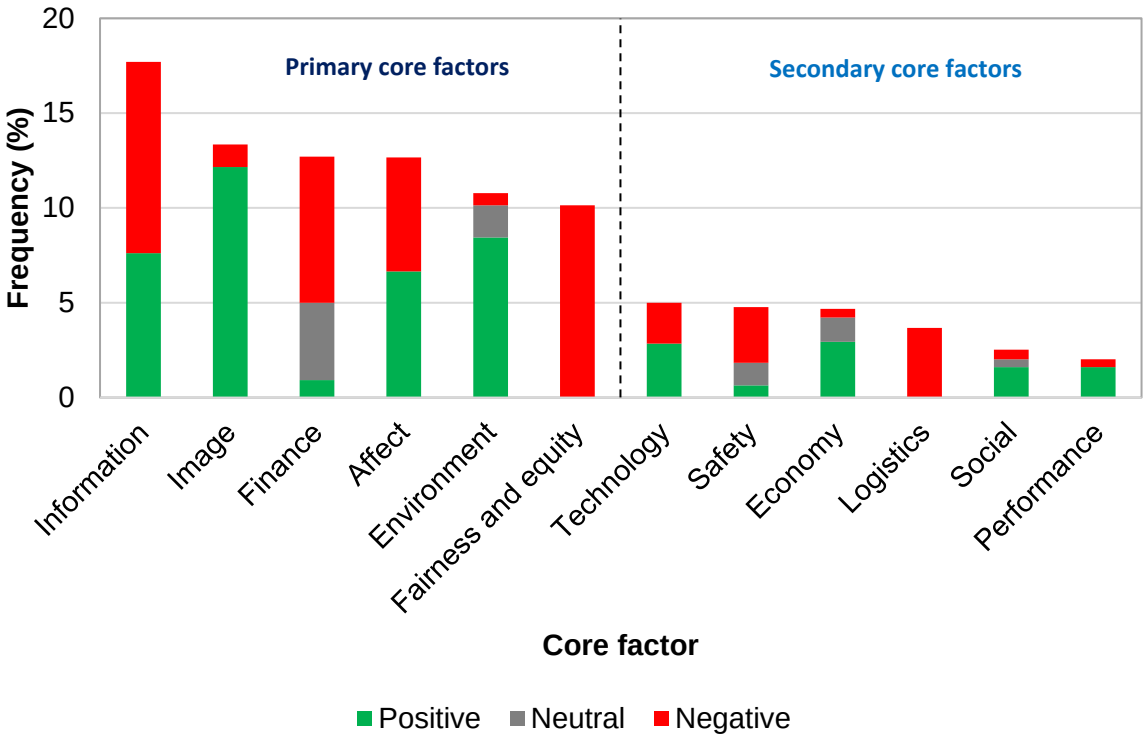


Fig. 3-4. Core factors influencing domestic hydrogen acceptance (full counting).

[1] As a way of checking for robustness at the outset of the analysis, the same calculations were performed using the mean score for each core factor across respective sub-groups. The classification remained unchanged among the primary factors and largely unaffected among secondary factors, confirming the validity of the demarcation: ***Information*** (16.9%); ***image*** (13.5%); ***finance*** (12.7%); ***affect*** (12.6%); ***environment*** (11.5%); ***fairness and equity*** (9.8%); ***economy*** (5.1%); ***safety*** (4.9%); ***technology*** (4.7%); ***logistics*** (3.4%); ***social*** (2.7%); and ***performance*** (2.2%).

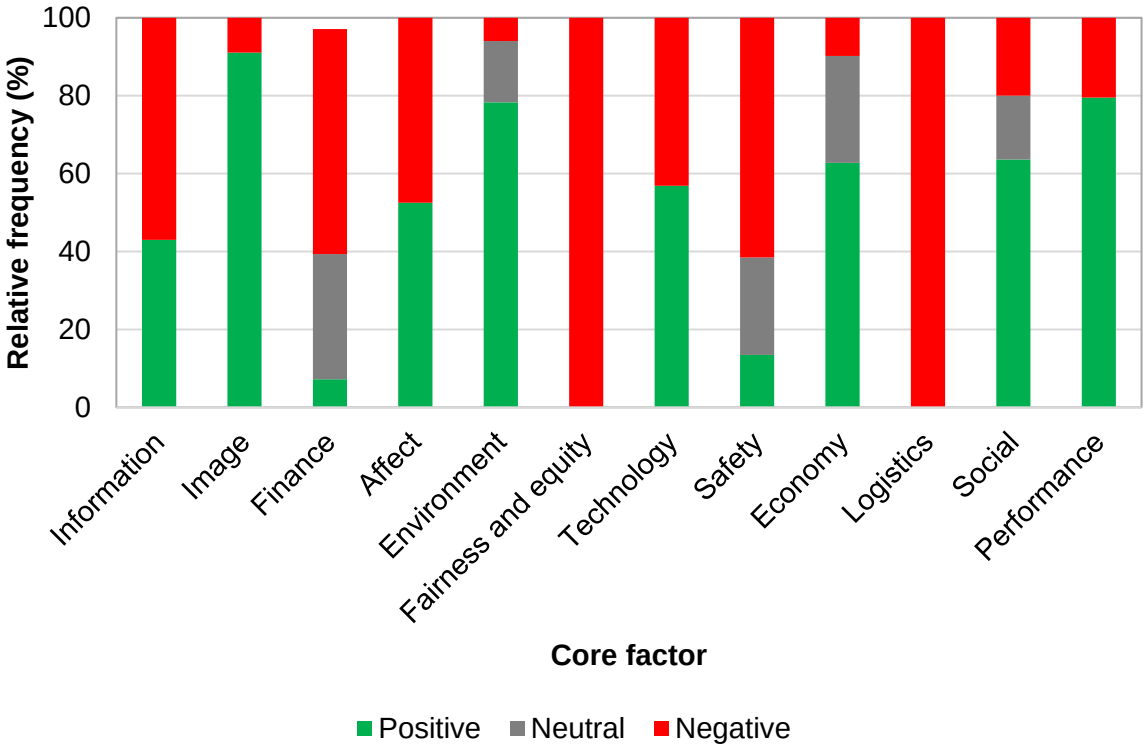


Fig. 3-5. Weighted analysis of core factors influencing domestic hydrogen acceptance (full counting).

3.4.1.2 Results from binary counting

In some cases, core factors (i.e. ***safety*** and ***performance***) were composed of sub-factors which had no level of overlap in relation to consumer responses. For example, in the case of ***safety***, respondents either recognised *safety benefits* or *safety risks*, or otherwise stated that their attitude was *contingent on safety implications*, which resulted in three mutually exclusive sub-factors (1 positive, 1 neutral, and 1 negative). For the most part, limited overlap occurred between core factors when analysed in terms of full counting and binary counting, except for ***information***, and ***fairness and equity*** (see Table 3-4).

Information presented high levels of overlap between *knowledge deficit* and *pro hydrogen information* (in general), whereby the former sub-factor motivated requests and desires for learning more about domestic hydrogen (see Section 3.4.3.1). In terms of ***fairness and equity***, given its composition as a solely negative core factor (see Fig. 3-5), just over a quarter of responses referred to at least two of seven available sub-factors, with a maximum of three sub-factors described (N = 9).

Overall, the number of references reduces from 2180 to 1935 (-11.2%) when applying binary counting. As a result, the rank order of factors presented in Fig. 3-6 deviates somewhat from Fig. 3-4, giving rise to an alternative classification scheme: primary core factors (≥10% of binary codes); secondary core factors (5–10% of binary codes); and tertiary core factors (≤5% of binary codes). Consequently, primary, secondary, and tertiary core factors represent 67.4%, 18.9%, and 13.7% of the coding results.

The main change reflected in Fig. 3-6 is near equivalence between the top four primary core factors, namely, ***image*** (14.5%), ***finance*** (13.9%), ***affect*** (13.5%), and ***information*** (13.4%), while ***environment*** is slightly less represented (12.0%). At the individual level, ***information*** drops from first rank to fourth when evaluated at the binary level, whereas five core factors undergo an adjustment of one position, while the remaining six factors remain unchanged. As a result, there is limited impact on the lower ranking core factors, however, there is clearer grounds for demarcating between the secondary and tertiary level, as reflected in Fig. 3-6 (see Fig. M-1 and Fig. M-2).

Adhering to the classification scheme and distribution criteria presented in 3.4.1.1 (see Table 3-3 and Fig. 3-4), Section 3.4.2 explores the composition and significance of core factors of domestic hydrogen acceptance, which are discussed in terms of respective sub-factors. The critical findings presented in Fig. 3-6 support the subsequent analysis in Section 3.5, which compares findings from this study to results in the literature.

Table 3-4. Comparison of coding results from full counting and binary counting.

Core factor	Full counting (%)	Binary counting (%)	Difference (%)	Overlap (%)
Information	386 (17.7)	260 (13.4)	126 (-4.3)	32.6
Image	291 (13.3)	281 (14.5)	10 (+1.2)	3.4
Finance	277 (12.7)	269 (13.9)	8 (+1.2)	2.9
Affect	276 (12.6)	262 (13.5)	14 (+0.9)	5.1
Environment	235 (10.8)	232 (12.0)	3 (+1.2)	1.3
Fairness and equity	221 (10.1)	162 (8.4)	59 (-1.7)	26.7
Technology	109 (5.0)	99 (5.1)	10 (+0.1)	9.2
Safety	104 (4.8)	104 (5.4)	0 (+0.6)	0.0
Economy	102 (4.7)	92 (4.8)	10 (+0.1)	9.8
Logistics	80 (3.7)	78 (4.0)	2 (+0.3)	2.5
Social	55 (2.5)	52 (2.7)	3 (+0.2)	5.5
Performance	44 (2.0)	44 (2.3)	0 (+0.3)	0.0

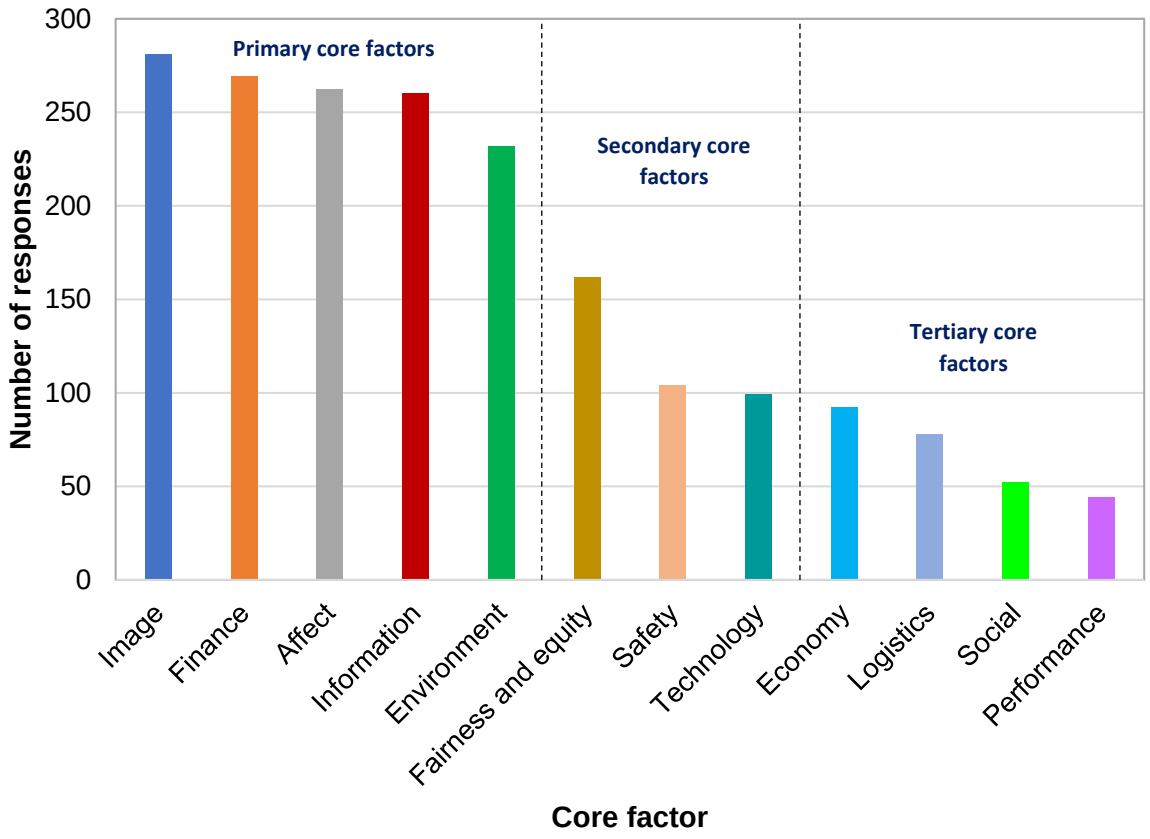


Fig. 3-6. Breakdown of core factors influencing domestic hydrogen acceptance (binary counting).

Selected colours represent a single factor to enhance readability.

3.4.2 Sub-factors of domestic hydrogen acceptance

In total, 48 sub-factors were identified, corresponding to a mean of four sub-factors per core factor (*SD* = 1.41). Specifically, each core factor consists of a minimum of two sub-factors (i.e. for ***affect*** and ***performance***), while seven sub-factors represents the upper limit (i.e. ***fairness and equity***). As reported in Table 3-3, the sub-factors were close to equally balanced in terms of positive (45.4%) and negative (45.9%) composition, while neutral responses accounted for a smaller proportion of the retrieved codes (8.7%).

The neutral category reflects five specific sub-factors corresponding to explicit expressions of contingency towards forming a positive or negative attitude. For example, the sub-factor *conditional on financial implications* is defined as follows: *Responses conveying the notion that forming a positive or negative attitude towards domestic hydrogen is contingent on financial implications, which were currently perceived to be indeterminate*. The same logic was applied to the remaining neutral

sub-factors, namely, *conditional on cost-of-living crisis*, *environmental implications*, *safety implications*, and *societal implications*.

The results of the neutral category are described in Appendix M (see Table M-3), given that such perceptions should, in theory, evolve over time to form a positive or negative perception. While neutral perceptions could technically remain recalcitrant or become potentially become more widespread overtime, this study concentrates foremost on exploring the main drivers and barriers to domestic hydrogen acceptance. However, an exception is the sub-factor *conditional on cost-of-living crisis*, which is a predictor of consumer heterogeneity and therefore discussed in Section 3.4.6.2.

Accordingly, each coding result adheres to a specific orientation or framing, which resulted in the following distribution: 17 positive, 5 neutral, and 26 negative sub-factors (see Table 3-5 and Table 3-6). To help analyse the results, the following cut-offs were applied to identify primary, secondary, and tertiary groups: sub-factors with a weighting above 5% (N = 8); between 1% and 5% (N = 15); and less than 1% (N = 25). Table 3-6 summarises the breakdown of sub-factors according to number of responses and classification (i.e. positive, neutral, or negative).

Table 3-5. Summary of sub-factors influencing domestic hydrogen acceptance.

			Breakdown of sub-factors		
	No. of codes (%)	**No. of Sub-factors (%)**	**Primary (%)**	**Secondary (%)**	**Tertiary (%)**
Positive	990 (45.4)	17 (35.4)	5 (33.8)	5 (7.9)	7 (2.8)
Neutral	190 (8.7)	5 (10.4)	0 (0.0)	4 (8.3)	1 (0.4)
Negative	1001 (45.9)	26 (54.2)	3 (23.4)	6 (13.4)	17 (10.0)
Total	2180 (100.0)	48 (100.0)	8 (57.2)	15 (29.5)	25 (13.3)

Table 3-6. Breakdown of factors influencing domestic hydrogen acceptance.

Core factors	**Sub-factors**	**Classification**	**Count and percentage**
Information	• Pro information about domestic hydrogen in general	• Positive	• 143 (6.6)
	• Knowledge deficit	• Negative	• 220 (10.1)
	• Pro information about hydrogen costs	• Positive	• 18 (0.8)
	• Pro information about hydrogen safety	• Positive	• 5 (0.2)

Image	• Fuel of the future	• Positive	• 110 (5.0)
	• Pro hydrogen concept	• Positive	• 154 (7.1)
	• Town gas experience	• Positive	• 1 (0.0)
	• Unpublicised status of hydrogen	• Negative	• 17 (0.8)
	• Negative social representation	• Negative	• 9 (0.4)
Finance	• Financial benefits	• Positive	• 20 (0.9)
	• Financial risks	• Negative	• 160 (7.3)
	• Conditional on financial implications	• Neutral	• 89 (4.1)
	• Boiler rejection due to recent investment	• Negative	• 7 (0.3)
Affect	• Positive emotions	• Positive	• 145 (6.7)
	• Negative emotions	• Negative	• 131 (6.0)
Environment	• Environmental benefits	• Positive	• 184 (8.4)
	• Environmental risks	• Negative	• 9 (0.4)
	• Net-zero scepticism	• Negative	• 5 (0.2)
	• Conditional on environmental implications	• Neutral	• 37 (1.7)
Fairness and equity	• Choice deficit	• Negative	• 28 (1.3)
	• Trust deficit	• Negative	• 28 (1.3)
	• Profit motives of energy companies	• Negative	• 13 (0.6)
	• Consumers shouldn't pay for the costs of the domestic hydrogen transition	• Negative	• 30 (1.4)
	• Government should pay the costs of the domestic hydrogen transition	• Negative	• 20 (0.9)
	• Energy companies should pay the costs of the domestic hydrogen transition	• Negative	• 21 (1.0)
	• Distributional injustice (general)	• Negative	• 81 (3.7)
Technology	• Pro technology or modern progress	• Positive	• 36 (1.7)
	• Pro Research & Development for hydrogen	• Positive	• 26 (1.2)
	• Pro alternative low-carbon options (not hydrogen)	• Negative	• 12 (0.6)
	• Risk aversion to new technologies	• Negative	• 21 (1.0)
	• Hydrogen perceived as an unproven technology	• Negative •	• 14 (0.6)
Safety	• Safety benefits	• Positive	• 14 (0.6)
	• Safety risks	• Negative	• 64 (2.9)
	• Conditional on safety implications	• Neutral	• 26 (1.2)
Economy	• Economic benefits	• Positive	• 21 (1.0)
	• Economic risks	• Negative	• 4 (0.2)
	• Energy security benefits	• Positive	• 43 (2.0)
	• Energy security risks	• Negative	• 3 (0.1)
	• Conditional on cost-of-living crisis	• Neutral	• 28 (1.3)
Logistics	• Age barrier	• Negative	• 3 (0.1)
	• Disruptive impacts	• Negative	• 16 (0.7)
	• Logistical risks	• Negative	• 61 (2.8)

Social	• Community benefits • Societal benefits • Societal risks • Conditional on societal implications	• Positive • Positive • Negative • Neutral	• 3 (0.1) • 32 (1.5) • 11 (0.5) • 9 (0.4)
Performance	• Efficiency or utility benefits • Efficiency or utility losses	• Positive • Negative	• 35 (1.6) • 9 (0.4)

3.4.3 Analysis of primary sub-factors

Primary sub-factors of domestic hydrogen acceptance account for 57.2% of the coding results. Five positive sub-factors compose 59.0% of the group, while three negative sub-factors account for the remainder. Overall, this breakdown corresponds to 33.8% and 23.4% of the coding results. *Knowledge deficit* (10.1%) represents the most prominent sub-factor, while *fuel of the future* qualifies as the least important, just above the cut-off (5.05%). The mean frequency for the primary group is 7.2% (*SD* = 1.54), with three sub-factors falling above this value (*knowledge deficit, environmental benefits,* and *financial risks*). In summary, the primary group represents five core factors, namely, ***information*** (x2), ***environment*** (x1), ***finance*** (x1), ***image*** (x2), and ***affect*** (x2). Accordingly, taking the cumulative contribution of primary sub-factors, the following breakdown is observed across the group: ***information*** (16.7%), ***affect*** (12.6%), ***image*** (12.0%), ***environment*** (8.5%), and ***finance*** (7.4%). This sequence retains the top five core factors illustrated in Table 3-3, with ***information*** preserved as the leading core factor, as reflected by *knowledge deficit* in Fig. 3-7.

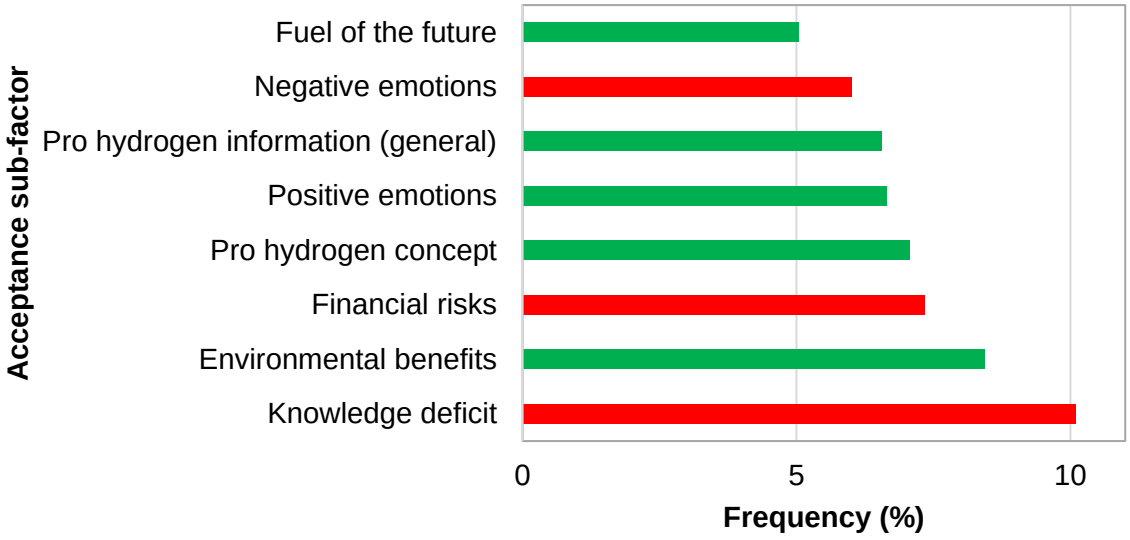


Fig. 3-7. Primary sub-factors of domestic hydrogen acceptance.

Green = Positive sub-factors; Red = Negative sub-factors.

3.4.3.1 Knowledge deficit and pro hydrogen information

Statements describing an underlying *knowledge deficit* in regard to hydrogen ranked as the highest primary sub-factor (N = 220). One respondent explained how they had "*not heard much about hydrogen apart from powering buses and trucks before…heard more about heat pumps*" (BLG 266), while another explained how "*it seems quite scientific and difficult to wrap your head around completely*" (VEG 139). Notably, the latter comment came from a participant with high levels of technology and environmental engagement. Another respondent specified how "*not enough is known about supplies of this and a lot of speculation is happening*" (FSG 158).

Multiple studies have highlighted risks and knowledge gaps around hydrogen energy systems, with an emphasis on technical and market barriers [188], the unpredictability of global supply chains for key components [189], as well as lack of skilled labour for scaling up development [190,191]. Above all, the results support previous findings highlighting an underlying knowledge deficit for hydrogen technologies across a range of national contexts [108,111,192,193]. For example, in the Australian context, Scovell and Walton [81] reported a mean subjective knowledge score of 2.33 (*SD* = 1.12) as measured on a seven-point Likert scale (1 = 'never heard of hydrogen energy technology', and 7 = 'very knowledgeable'). Similarly, following data collection in Spring of 2022 (N = 4372), the UK government reported relatively low levels of hydrogen awareness (*M* = 2.44, *SD* = 1.11) as measured on a five-point Likert scale [194].

While a public knowledge deficit is somewhat pervasive but potentially declining over time [195], consumers also have an expressed preference for learning more, as reflected by a *pro hydrogen information* perspective (N = 143), which in some cases corresponded to specific requests for information on safety and costs (see Table 3-6 and Fig. M-3). Comments included a mix of admissions and affirmations such as the following: "*I don't know enough to form a complete opinion, but I will look into it more*" (BLG90); "*I'm still very new to the concept but will definitely be learning more*" (BLG171); "*I do need to be more informed on the subject*" (BLG73); and "*I am going to do more research*" (BLG61). In some cases, respondents also expressed a more explicit desire, for example, "*I would love to learn more about it*" (BLG164).

Finally, it should be noted that significant overlap was observed between the two sub-factors, with nearly 41% of responses expressing an underlying lack of knowledge, which motivated a call for more information on hydrogen. This pattern may reflect a wider feeling among society to learn more about emerging clean energy technologies.

3.4.3.2 Environmental benefits

Environmental benefits ranked as the second primary sub-factor and first in terms of positive sub-factors, with around three-quarters of references (N = 137) linking more explicitly to hydrogen's potential impacts (i.e. beyond a generic comment such as 'good' or 'better' for the environment). To an extent, direct references to planetary impacts mirrored the overall discussion of environmental benefits (see Section 3.4.6.1), whereby the MEG (N = 46) and VEG (N =40) accounted for nearly two-thirds of references (62.8%), while the BLG (N =26) and FSG (N = 25) accounted equally for the remainder of responses.

Several sub-codes emerge following analysis of qualitative response patterns, which in many cases share degrees of similarity or overlap. For example, regarding hydrogen's potential role in decarbonisation, respondents referred to *green energy*, *sustainable fuel*, *clean energy*, *alternative fuel*, and *renewable energy*. In total, nine themes were identified (see Fig. 3-8), with *climate change* ranking first, whereas *carbon emissions* placed fourth.

Interestingly, relatively few participants made explicit reference to *net zero*, which may reflect a lower level of consciousness and engagement with this term among the public. By comparison, around double the number of respondents articulated the need to *save the planet*. This planet-centric perspective towards hydrogen or "*long-term, save the planet kind-of-feeling*" (MEG 157) was described vividly by one respondent:

> "*It has to be the way forward to reduce carbon emissions and try to heal the world. Anything that can make things better for the climate and still be sustainable is a step in the right direction"* (FSG 123).

By contrast, other respondents looked towards a sustainable future with economic growth, which could foreseeably prove incompatible with climate change targets [196,197]:

> "*It has potential to have a significant impact not only on this country but globally too. We are currently in unseen circumstances, so hydrogen-powered options*

seem like something that is sustainable and allows growth moving forward" (MEG 176).

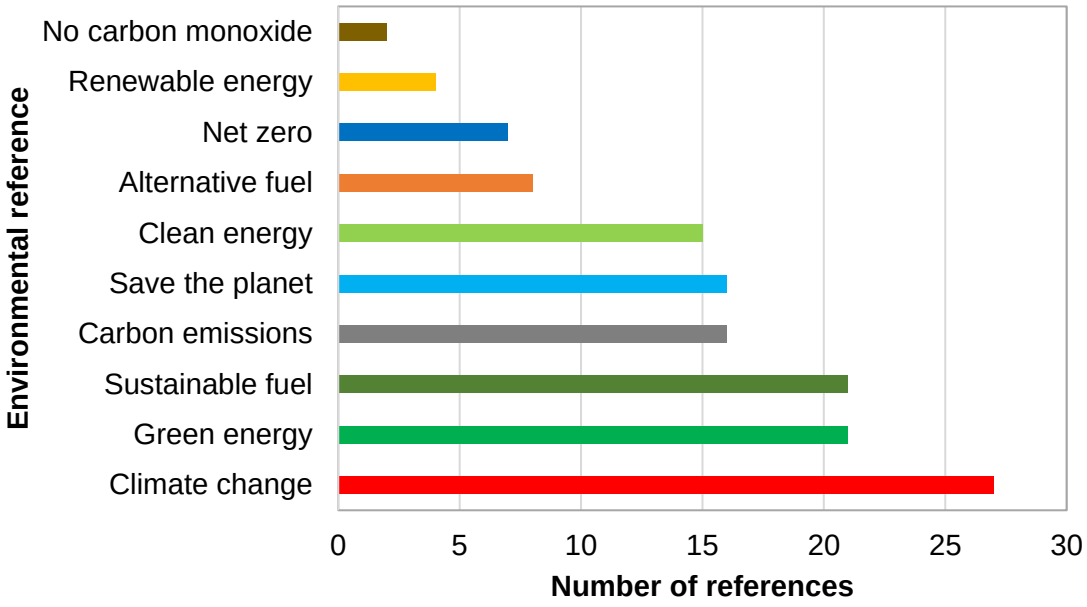


Fig. 3-8. Distribution of consumer responses citing specific aspects of environmental benefits.

Selected colours represent a single factor to enhance readability.

3.4.3.3 Financial risks

Consistent with qualitative results [106] and literature review findings [77], *financial risks* associated with the purchasing and running of hydrogen appliances emerged as the third most critical sub-factor of domestic hydrogen acceptance. Epitomising concerns over this aspect, one fuel poor respondent cautioned, "*I cannot afford to heat my house, let alone think about replacing a boiler, which I still haven't finished paying off since I got it replaced*" (FSG 40). Foremost, consumers facing fuel poverty may be forced to prioritise cost considerations above other factors when considering domestic hydrogen adoption.

Other sub-groups considered that hydrogen "…*would prove too expensive to run and cause more poverty for families for their heating and cooking*" (BLG 7). Broadening these perspectives to the context of the macro-economic and political environment, one participant declared their resistance to the prospect of hydrogen homes:

> "*I would not be happy paying towards this as it is going to be incredibly costly. Given we are in a cost-of-living crisis, I'm not sure where the government think*

people will get the money from when they can't even pay their gas bills or get their boiler serviced!" (BLG 166).

Drawing attention to financial, as well as equity-related barriers [49], opposition to the prospect of hydrogen boilers and UK policy was voiced on the following grounds: "*…vastly expensive and ignores the reality of the older UK housing stock. I'm not paying 10k for a boiler, so no heat for me, although I'll be expected to subsidise others*" (BLG 346). Taken as a snapshot, these remarks flag the likelihood, if not inevitability, that domestic hydrogen acceptance will boil down to financial considerations for a significant proportion of society [198].

3.4.3.4 Pro hydrogen concept and fuel of the future

In terms of image, *pro hydrogen concept* ranked as the fourth primary sub-factor, while *fuel of the future* ranked tenth. The former sub-factor refers to responses citing positive prospects for hydrogen in the long-term, often referring to its definitive role as a future fuel. By contrast, the latter sub-factor corresponds to responses citing the positive value of hydrogen, as a general concept for potentially supporting the energy transition. In the Australian context, Scovell and Walton [81] noted a similar perspective in acknowledging that "some [focus group] participants thought that using more hydrogen seemed like a future solution as there needs to be more technological progress," which also links to the secondary sub-factor, *pro technology or modern progress*.

Regarding participant statements, one respondent described hydrogen as "*the future of fuel,*" which "*should be used and provided with the best interest of the country, households and the environment*" (MEG 186). Others described it as follows: "*a solution to switch to for energy in the future*" (BLG 134); "*the next step in energy*" (BLG 208); "…*the way forward…to wean ourselves off fossil fuels*" (VEG 81); "…*part of a plan to get the people in the UK to change towards a greener society*" (FSG 122); and "*a positive thing that's going to influential for the future*" (MEG 207).

Regarding the concept of hydrogen homes, a fuel poor participant shared their optimism as follows: "*I think this is a great idea and will hopefully reduce energy bills and the over reliance on rogue states who we rely on at the moment for our gas and energy needs. Great, simply fantastic*" (FSG 91). Among the VEG, respondents shared similar lines of thought, for example, "*I think that introducing hydrogen into*

homes is a good idea and will boost the economy as well as the environment" (VEG 98), and "*I think this is an amazing idea and it will help the UK develop a lot*!" (VEG 100). Other notable statements included, "*I think it is a great idea and hope it comes to my local area*" (VEG 86), and "…*very good idea and the government should give more details about it on TV so we are aware*" (VEG 194).

3.4.3.5 Positive emotions and negative emotions

Positive emotions ranked as the fifth primary sub-factor, while negative emotions ranked seventh. Foremost, respondents made generic references to hydrogen as 'positive', either for the environment, society, or the future, among other framings (N = 57). In addition, participants expressed optimism (N = 23), happiness (N = 15), interest (N = 14), excitement (N = 12), hopefulness (N = 10), eagerness (N = 8), and in some cases, love (N = 3), curiosity (N = 2), and confidence (N = 1).

For example, hope and excitement were shared and justified along similar lines: "*it sounds exciting and will hopefully be efficient and environmentally friendly*" (FSG 131); "*I am excited that hydrogen could replace gas and hopefully help towards the climate change. Also hope it helps the UK to become more self-sufficient and not rely on gas from other countries*" (MEG 49); and "*exciting and hopeful for a cleaner energy source and less reliance on foreign gas*" (BLG 34).

Around half of all negative responses were communicated in terms of 'concern' or 'worry', which were coded separately to reflect the language used by respondents. Other notable feelings included *confusion*, *nervousness*, and *fear* (see Fig. 3-9), whereas expressions of *scepticism* or *pessimism* were more limited. Excluding *concern* and *worry*, responses which were close synonyms were subsumed under one specific emotion, for example, *nervous* included 'apprehensive', 'hesitant', 'reluctant', 'uncomfortable', and 'uneasy', while *fear* included 'afraid' and 'scared'.

One respondent illuminated their concerns as follows:

> "*I have two main concerns. The first is that we'll stick with grey and blue hydrogen indefinitely. I do not trust the Westminster government. Second, I feel in the domestic situation hydrogen has some serious safety issues. I'd prefer electric solutions to domestic heating and cooking*" (VEG 70).

Another respondent shared a range of worries:

> "*Worried it might be expensive. Not sure about reliability, plus repair and maintenance cost will be higher, as it's a new concept. In terms of house use installation, there will be flaws that will take years to perfect*" (FSG 206).

Negative emotions also originated from fears of the new and unknown, "*feel quite nervous thinking about, probably because it's something new*" (BLG 37), while another respondent reflected further on the unfamiliarity of hydrogen fuel [199]:

> "*The fear of the unknown - we have only ever been used to "normal" gas - therefore the prospect of a new hydrogen gas can be a scary thought when we, as normal working people, don't know much about how or when this will affect us*" (BLG 322).

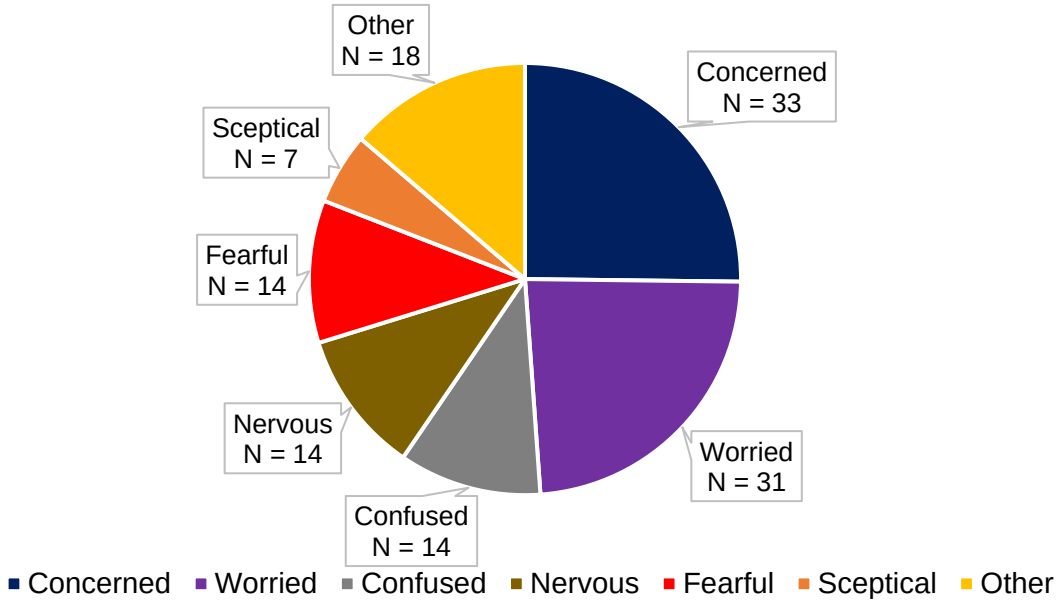


Fig. 3-9. Distribution of negative emotions across the sample (N = 131).

3.4.4 Analysis of secondary sub-factors

Following the primary category, 15 secondary sub-factors of domestic hydrogen acceptance account for 29.5% of the coding results (see Fig. 3-10). Six negative sub-factors compose 45.3% of this group, whereas five positive sub-factors and four neutral sub-factors account for 26.7% and 28.0%, respectively. Taken together, secondary sub-factors represent nine core factors: ***economy*** (x2), ***environment*** (x1), ***fairness and equity*** (x4), ***finance*** (x1), ***logistics*** (x1), ***performance*** (x1), ***safety*** (x2), ***society*** (x1), and ***technology*** (x2).

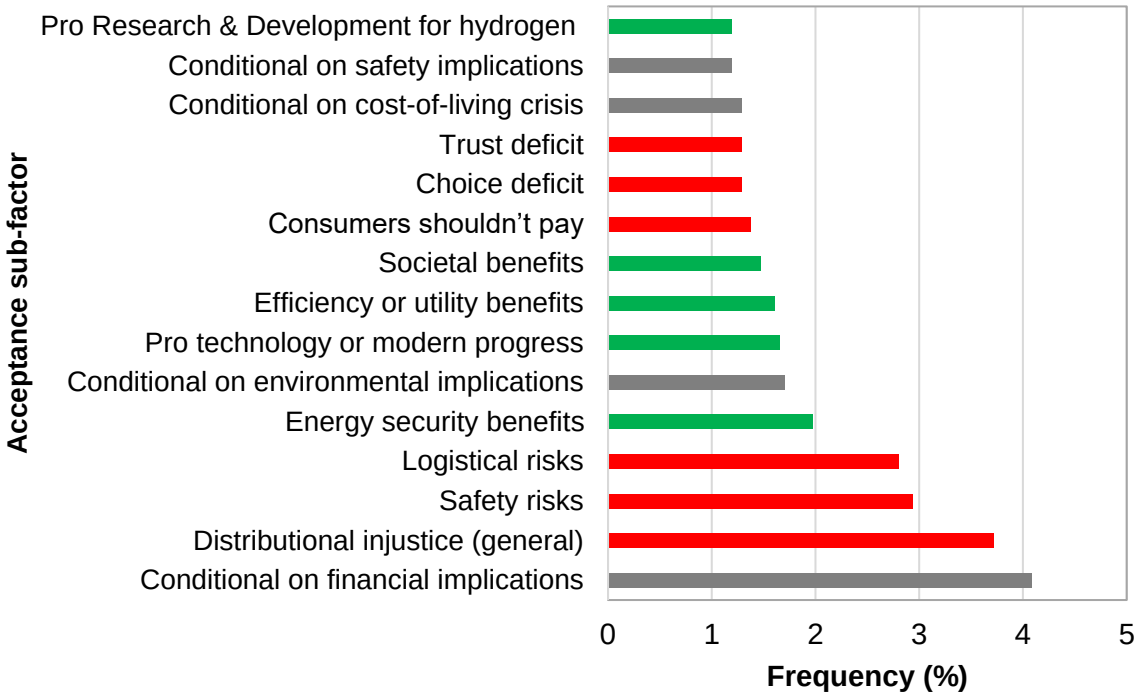


Fig. 3-10. Secondary sub-factors of domestic hydrogen acceptance.

Green = Positive sub-factors; Grey = Neutral sub-factors; Red = Negative sub-factors.

3.4.4.1 Positive secondary sub-factors

Positive secondary sub-factors include *efficiency or utility benefits* (***performance***), *energy security benefits* (***economy***), *pro technology or modern progress* (***technology***), *pro research and development for hydrogen* (***technology***), and *societal benefits* (***social***).

Survey responses linked to aspects of ***performance***, ***economy***, and ***finance*** reflect how the sub-par efficiency performance of the UK housing stock [26,200], coupled to the ongoing energy and deepening fuel poverty crises [106,201–203], will shape consumer expectations for the hydrogen switchover. For example, performance expectancy for domestic hydrogen [135] was framed as follows: "*I want it as a more sustainable alternative to gas and assume it would perform better than electric heating and hobs*" (VEG 103); and "*I consider hydrogen gas more efficient in our daily lives*" (VEG 62).

Interestingly, one respondent perceived hydrogen as a better option over electric alternatives, "…*this means the least disruption and modifications to a house at the moment that currently uses gas*" (VEG 143). Additionally, a fuel stressed participant

declared, "*it's clear that hydrogen is an efficient energy source that should be cheaper for consumers than gas*," (FSG 134) while another respondent shared an optimistic outlook, "*I am looking forward to finally living and bringing up my daughter in a safer and more efficient home*" (BLG 66).

It follows that consumer acceptance will be partly dictated by the degree to which hydrogen can secure a more efficient and reliable energy supply to UK homes, as a potential means for alleviating fuel poverty and economic hardship. However, realising the promise of a national hydrogen economy [204] will rest heavily on the pace at which a domestic hydrogen supply chain can be established, alongside addressing other market barriers and a range of techno-economic, technical, social, and political barriers [26]. Speaking to the need for technological progress, some respondents also cited the requirement to intensify *research and development* for hydrogen (N = 26), or otherwise expressed general optimism for advancing a more socio-economically viable future by investing resources in the hydrogen economy [75].

3.4.4.2 Negative secondary sub-factors

Negative secondary sub-factors include *safety risks* (***safety***), *logistical risks* (***logistics***), and four aspects of ***fairness and equity*** (*distributional injustice in general*, *consumers shouldn't pay*, *choice deficit*, and *trust deficit*). The next sub-sections tackle each of these areas, with a focus on qualitative statements and supporting data analysis.

3.4.4.2.1 Logistical risks

Logistical risks accounted for close to 3% of all references to acceptance factors, placing fourth among the secondary group of sub-factors (see Fig. 3-10). Notably, participants flagged concerns about the techno-economic feasibility of the switchover in relation to cost factors and scalability [49], describing hydrogen homes as, "*a potential good solution with many technical and infrastructure challenges to be overcome*" (MEG 1), which "will *present a major engineering and logistical challenge costing billions*" (MEG 119).

Both the scale and cost of the challenge were highlighted in other remarks, for example, "*insufficient supplies to switchover and in the end, consumers have to foot the bills*" (BLG 193), and "*seeing as big schemes bring big mistakes is my main concern…it's a good energy but installing it across the country is the worrying point*"

(BLG 293). Other respondents were sceptical or critical about potential energy requirements, "*it seems to be a technology worth exploring, but the case for it is far from compelling due to the high energy required to produce it*" (MEG 195) and "*it will need more electricity to generate hydrogen*" (FSG 132). Relatedly, one respondent saw advantages with other energy sources, "*I feel like as much as hydrogen is a viable future energy source, I do feel that nuclear and renewables are a lot more feasible and cost efficient*" (VEG 64).

Another participant noted advantages in targeting better insulation for homes ahead of adopting low-carbon technologies, "*might be useful to insulate homes first*" (MEG 222), while one respondent noted the challenge related to market factors, "…*needed for the future but will take some time to adapt business models*" (VEG 168). Both points are on the radar of UK policy makers [205], with the Heat and Buildings Strategy [21] calling for measures to improve the thermal efficient of homes such as draught-proofing and other types of insulation, while the government is actively pursuing a certification scheme to help build transparency and confidence across the hydrogen sector [206]. Overall, this study suggests that the disruptive impacts of the domestic hydrogen transition are a moderate factor in shaping consumer attitudes, which is in line with prior findings in the UK context [106,207].

3.4.4.2.2 Safety risks

Reflecting the extant narrative concerning technical barriers to implementation [49,208–210], *safety risks* associated with hydrogen were cited over four times more frequently than *safety benefits*. From the 62 references to safety concerns, around half concentrated on particular risk perceptions, with most respondents describing hydrogen as *dangerous*, while some specified these dangers in terms of explosions and high flammability (see Fig. 3-11).

Overall, safety-related concerns were associated with hydrogen's inherent characteristics as a highly flammable, colourless, and odourless gas [211], which led to outright rejection among some respondents. One respondent felt "*not very comfortable with something so flammable*" (MEG 151), while another was "*fearful of explosiveness*" (VEG 26), with a third citing further reservations, "…*safety wise I would be reluctant to use this…the images of the hydrogen balloons igniting come to mind*" (MEG 242). This respondent was not alone in expressing a negative social

representation. For example, other responses linked hydrogen to nuclear power, "*I always associate hydrogen with nuclear, probably why I am not overly enthusiastic*" (MEG 44), and "…*still unsure, like before fearful of nuclear explosion*" (FSG 177).

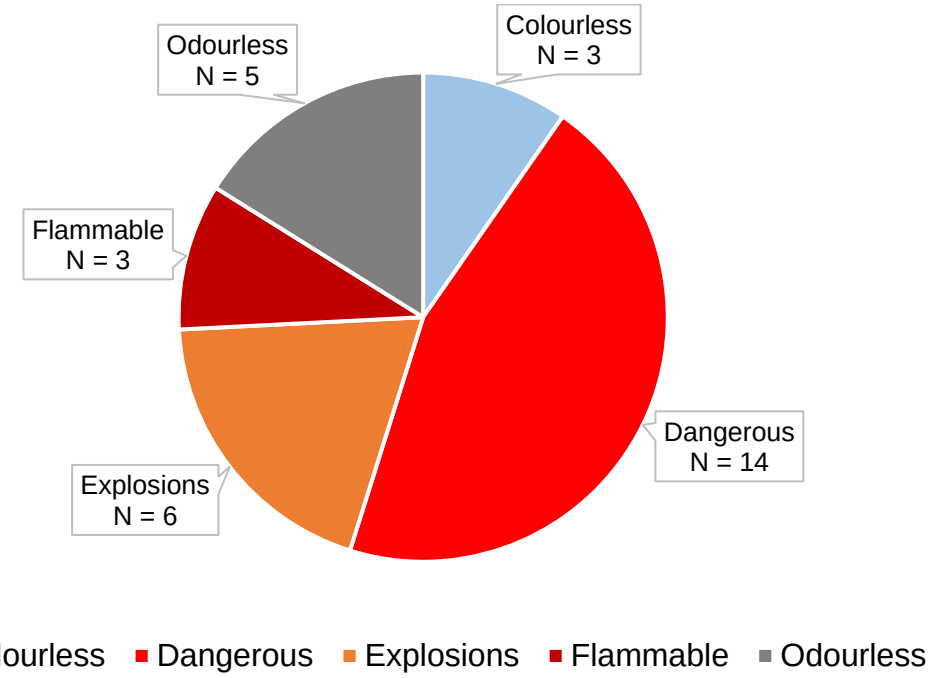


Fig. 3-11. Responses citing specific risk perceptions around hydrogen safety.

Regarding the characteristics of hydrogen, one respondent noted a technical issue which the scientific community are invested in resolving, through the addition of odourants as well as colourants [24,47,212]: "*the only slight concern I have is the fact it is odourless, so I am unsure if people would be able to detect gas leaks through smell*" (VEG 184). Additionally, one technically minded participant was "*concerned about safety and the problems of brittleness when components are exposed to hydrogen over an extended period*" (VEG 17), whereas a baseline respondent felt "*scared as no controls appear to be in place for safety issues*" (BLG 290).

While several technical solutions are foreseeable [188,213–215], negative safety perceptions must be addressed and overturned if hydrogen is to have a place in the future energy mix beyond industrial applications [28]. Otherwise, the following perception could prevail among wider society ahead of more substantive evidence, "*from what I understand, hydrogen is very dangerous, and it wouldn't be advisable for use in the general public*" (MEG 24).

3.4.4.2.3 Perceptions of fairness and equity

Fairness and equity concerns accounted for 26% of secondary sub-factors, focusing primarily on aspects of *distributional injustice* [216,217]. Insightfully, one participant articulated their concerns in significant detail, contextualised to the discussion around industrial reinvigoration [106] and the North-South divide [218,219]:

> "*Suggestions of how the technology is funded has the potential to widen the inequality gap in my opinion. It's interesting that early implementation sites are proposed around areas of denser industrialisation. It seems to me that these populations are not only more likely to be poor but may be carrying a disproportionate legacy of ill health from historical industrialisation. Introducing 'experimental' technologies here seems somewhat unethical, particularly if there is no financial incentive to accept them. Requiring these populations to pay for the technology, thus feeding into its development going forward, seems rather unfair*" (MEG 250).

Another respondent from the BLG also captured these concerns succinctly:

> "…*I worry about the cost to low-income earners. I would be happy for it to be rolled out in industrial towns first, but these are low earners so sorry it would hit them hardest. Some info on what modelling shows the predicted costs would be per household would be good*" (BLG 360).

Such perspectives affirm that stakeholders will need to mitigate the risks associated with distributional injustice to facilitate a socially acceptable transition to hydrogen homes [26]. These risks will be heightened when a *trust deficit* is present among consumers and if they perceive a lack of choice (i.e. *choice deficit*) regarding the prospective transition to hydrogen homes (see Section 3.4.5), as highlighted via online focus groups with UK participants [106].

Regarding the costs of the domestic hydrogen transition, several respondents believed *consumers shouldn't pay*, while others specified that *the government* and/or *energy companies should pay.* Notably, placing the financial onus of the hydrogen switchover on energy companies links directly to an associated tertiary sub-factor, namely, *profit motives of energy companies* (see Section 3.4.5).

Grievances towards profiteering were cited across all sub-groups, suggesting that this phenomenon threatens hydrogen acceptance irrespective of one's personal status. Moreover, a greater number of respondents raised further issues linked to aspects of energy injustice [112], such as lack of consent (procedural injustice) [220] and

hardships incurred by vulnerable households (recognition injustice) [221], among other matters concerning social fairness (see Table 3-7). These risks will be heightened when a trust deficit is pervasive among consumers, coupled to perceptions of a lack of choice regarding the prospective transition to hydrogen homes [106].

Table 3-7. Consumer perspectives citing aspects of energy injustice.

Respondent ID	Illustrative statements
BLG 13	• *As usual rural dwellers will miss out and should not have to pay for city dwellers benefits*.
BLG 92	• *I don't think that people living in areas where there is an unlikely possibility that they will ever be supplied with this new fuel source should pay for it*.
MEG 36	• *Hydrogen changeover should be encouraged, but I am very sceptical about the costs involved. These should be borne by the energy companies who are already making massive profits. Stop paying massive salaries and bonuses and dividends and invest in the future*.
VEG 49	• *I am all for replacing gas appliances, but UK households are under a lot of economic pressure as it is and the government keeps ignoring that pressure, especially to the middle class. It has to be affordable to switch*.
FSG 45	• *I don't feel that people who will never use this energy source should pay towards its development*.

3.4.4.3 Perceptions of choice and trust dynamics

Comments highlighting mistrust (*trust deficit*) and concerns over a lack of choice (*choice deficit*) were mentioned at the same frequency, suggesting that both sub-factors may present similar barriers to consumer acceptance. For example, one respondent facing fuel poverty declared, "*I don't trust the energy companies, so I'm not going green. You will have to force me*" (FSG 50). A fellow respondent voiced similar concerns regarding an absence of procedural justice, "*I think it is all being rushed through, and the public are being forced to use these things without all information being supplied*" (FSG 76). Scepticism and pessimism prevailed in the eyes of another fuel poor respondent:

> "*I am very pessimistic about any promises made by government, and I feel the outright cost will not be achievable for most households due to the current cost-of-living crisis. It is too little too late*" (FSG 38).

Further concerns were cited around choice and procedural injustice, "*I think consent is a vital issue here, as in, people shouldn't be made to pay for things if they don't want them*" (BLG 140). Another respondent cautioned, "*there needs to be more information, especially regarding other energy sources such as underground heat pumps in order*

to make fully informed decisions" (BLG 328). Concerns over decision-making aspects were particularly emphasised, "*It's very worrying but it's likely that these decisions will be taken by central government which means the public will not have a say in the matter*" (BLG 232), and "…*people shouldn't be forced to have it*" (BLG 240). As reported in Table 3-8, The main trust deficit expressed among respondents pertained to the shortcomings of the UK government, with no shortage of pessimistic and sceptical remarks.

Table 3-8. Consumer perspectives citing a trust deficit in the UK government.

Respondent ID	Illustrative statements
BLG 185	• *I'll wait and see, I'm afraid I have no confidence in government timetables now Boris* [Johnson] *has gone.*
BLG 256	• *If we still have a Tory government in power for years to come, then I'll be very sceptical that they'll make any effort to use this whole situation to the general public's advantage*.
BLG 303	• *I think the government are too incompetent to speed it up*.
MEG 88	• *Honestly, I don't have much faith and trust in the UK government*.
MEG 182	• *I don't trust the government to actually do it*.
MEG 193	• *I've no doubt it will be done in the most cynically and prohibitively expensive way possible*.
MEG 198	• *Can we trust any government to say they will do what they say they will regarding transition over to carbon-free boilers*?
VEG 70	• *I do not trust the Westminster government*.
FSG 22	• *Government using conflicting and confusing language to alienate most of the general public*.
FSG 38	• *I am very pessimistic about any promises made by government*.
FSG 46	• *I don't trust anything the government is pushing*.

3.4.5 Analysis of tertiary sub-factors

A group of 25 sub-factors – each with a frequency of less than one percent – account for the remaining responses (13.3%). Foremost, 17 negative factors represent 68.5% of tertiary level responses, compared to 28.4% for positive responses and 3.1% for the single neutral sub-factor (i.e. conditional on societal implications), as reported in Appendix M (see Fig. M-3).

All core factors were represented within the tertiary group except for ***affect***. ***Economy***, ***fairness and equity***, ***image***, ***social***, and ***technology*** featured most prominently, represented by three respective sub-factors. Next, ***environment***, ***finance***, ***information***, and ***logistics*** were represented by two sub-factors each, while ***performance*** and ***safety*** featured a single sub-factor. Foremost, the above

distribution highlights how a multitude of potential barriers could shape domestic hydrogen acceptance across different parts of society.

Within the tertiary group, several sub-factors were identified which could prove more prevalent across parts of the UK population, depending on relevant socio-structural and contextual factors [77]. For example, the *profit motives of energy companies* [222] is an increasingly polemic issue [223,224], given the cost-of-living crisis [201,202] and recent economic climate in the UK [225,226].

Several participants engaged with this aspect of renewable energy acceptance (see Table 3-9), with some observations linking directly to the role of government: "*the government should be paying for most of this swap over, as well as energy companies. This is due to the massive profits that these companies make, and no doubt will continue to make*" (BLG 324); and "…*want government and industry to get off their backsides and provide households with green solutions. Make the roll out better planned and moderated than solar panels please*" (VEG 197).

By extending the discussion beyond primary and secondary sub-factors of domestic hydrogen acceptance, this part of the analysis further demonstrates how a multitude of different variables may operate to varying degrees (see Fig. M-3); as shaped by underlying spatio-temporal and socio-historical factors [26,88,141], and the context-specific nature of domestic energy acceptance [92]. Having reviewed the breakdown of core and sub-factors across the sample, Section 3.4.6 extends the analysis by determining which factors influence consumer heterogeneity.

Table 3-9. Consumer perspectives citing grievances over the profiteering of energy companies.

Respondent ID	Illustrative statements
BLG 22	• *Cost is critical, people need to have a choice when it comes to financial commitments. Subsidising the cost using corporation tax would help people.*
BLG 358	• *We shouldn't be paying to put huge profits into different energy companies.*
BLG 363	• *With billions of pounds in profit, the costs could be covered by the main beneficiaries - the energy companies.*
MEG 107	• *I like the idea of using hydrogen as alternative to current gas. I believe it should be the current gas suppliers that should contribute to the changes to the infrastructure and switchover, not general public. They already have huge profits as it is.*

MEG 153	• *I'd love the chance to use this power source, but I also think that the costs should be shared by the power companies as they will ultimately benefit from sales/profits.*
MEG 155	• *If government/taxpayer funded, private companies should not profit from it.*
MEG 199	• *It sounds like something else for the energy companies to make more money out of the customer and bills will go up even more!*
MEG 254	• *The energy companies that run the distribution networks and British Gas make enough profits to pay for it. You will still be using the same distribution network pipeline. You won't have to change that, it will just be like when we went from coal gas to natural gas, most of the old pipeline has been renewed now.*
VEG 50	• *I am concerned that there is so much emphasis on householders paying for this. Why is there no suggestion that energy companies should be stumping up for the majority of the conversion from the excess profits they are currently in receipt of. The order of priority always seems to place householders at the top of the list.*
VEG 129	• *It's going to be expensive, but the energy company should accommodate the cost.*
VEG 182	• *The costs of any change over should be met by the companies that will receive obscene future profits.*
FSG 179	• *The energy companies are making vast profits. They should fund this.*
FSG 195	• *Those making a profit from sales should pick up the tab for implementing.*

3.4.6 Predictors of consumer heterogeneity

To derive additional insights into the configuration of consumer preferences and the influence of salient acceptance factors, Section 3.4.6 examines the foremost predictors of consumer heterogeneity. The analysis involves examining statistical differences between sub-groups by accounting for all sub-factors classified as primary or secondary, while tertiary sub-factors are excluded due to sample size constraints (see Table M-4 and Fig. M-3).

In total, nine sub-factors proved statistically significant, which were equally distributed between the 1% level ($\rho < 0.01$), 5% level ($\rho < 0.05$), and 10% level ($\rho < 0.10$). Cumulatively, this group of sub-factors account for 46.8% of total references, with the following breakdown within sub-groups: BLG = 49.8% (N = 389); MEG = 46.7% (N =282), VEG = 40% (N = 160); and FSG = 47.8% (N = 189). It follows that sub-factors explaining consumer heterogeneity account for close to half of all references within the dataset, reflecting some of the foremost drivers of hydrogen acceptance, including the three most salient sub-factors: *knowledge deficit*, *environmental benefits*, and *financial risks*.

To capture these dynamics, Fig. 3-12 illustrates the reported sub-factors according to relative frequency between sub-groups, wherein *environmental benefits* ranks first ($\rho < 0.001$), and positive emotions ranks last ($\rho = 0.079$). Accordingly, the group is composed of the following core factors: ***environment*** (x1), ***information*** (x1), ***finance*** (x1), ***fairness and equity*** (x2), ***economy*** (x2), and ***affect*** (x2). Additionally, Fig. 3-13 extends the analysis by comparing the relative importance (i.e. total number of references) of each sub-factor across consumer segments, wherein *knowledge deficit* ranks first, and *choice deficit* ranks last. Notably, *choice deficit* does not register as a sub-factor for the VEG (see Section 3.4.6.2).

Taken together, Fig. 3-12 and Fig. 3-13 highlight which aspects of domestic hydrogen acceptance could resonate distinctly across parts of the population, and thereby lead to different response patterns and outcomes, both within and between different regions of the UK such as the Northwest and Northeast of England where activities for hydrogen trials are targeted [18].

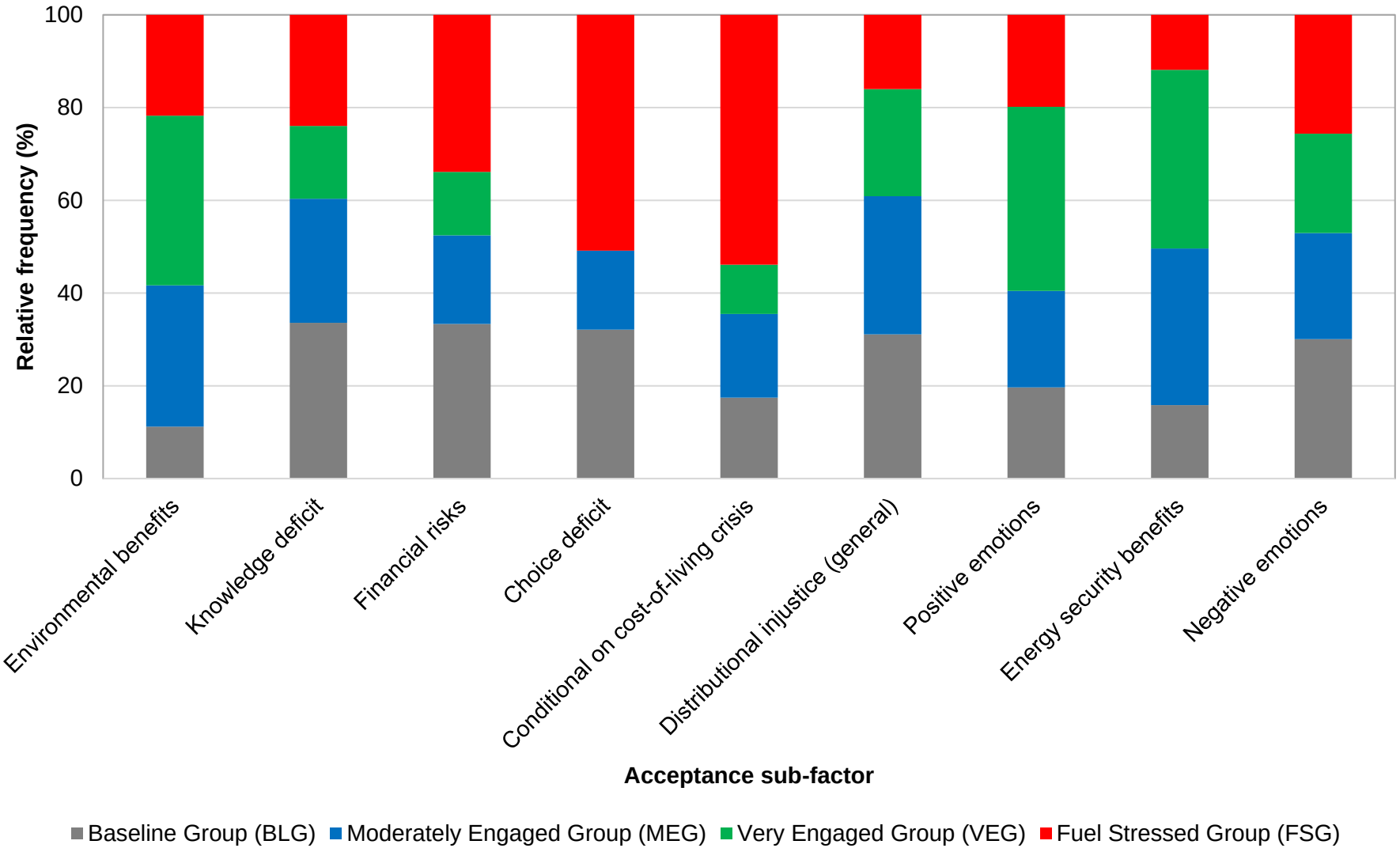


Fig. 3-12. Sub-factors explaining consumer heterogeneity ranked according to statistical significance.

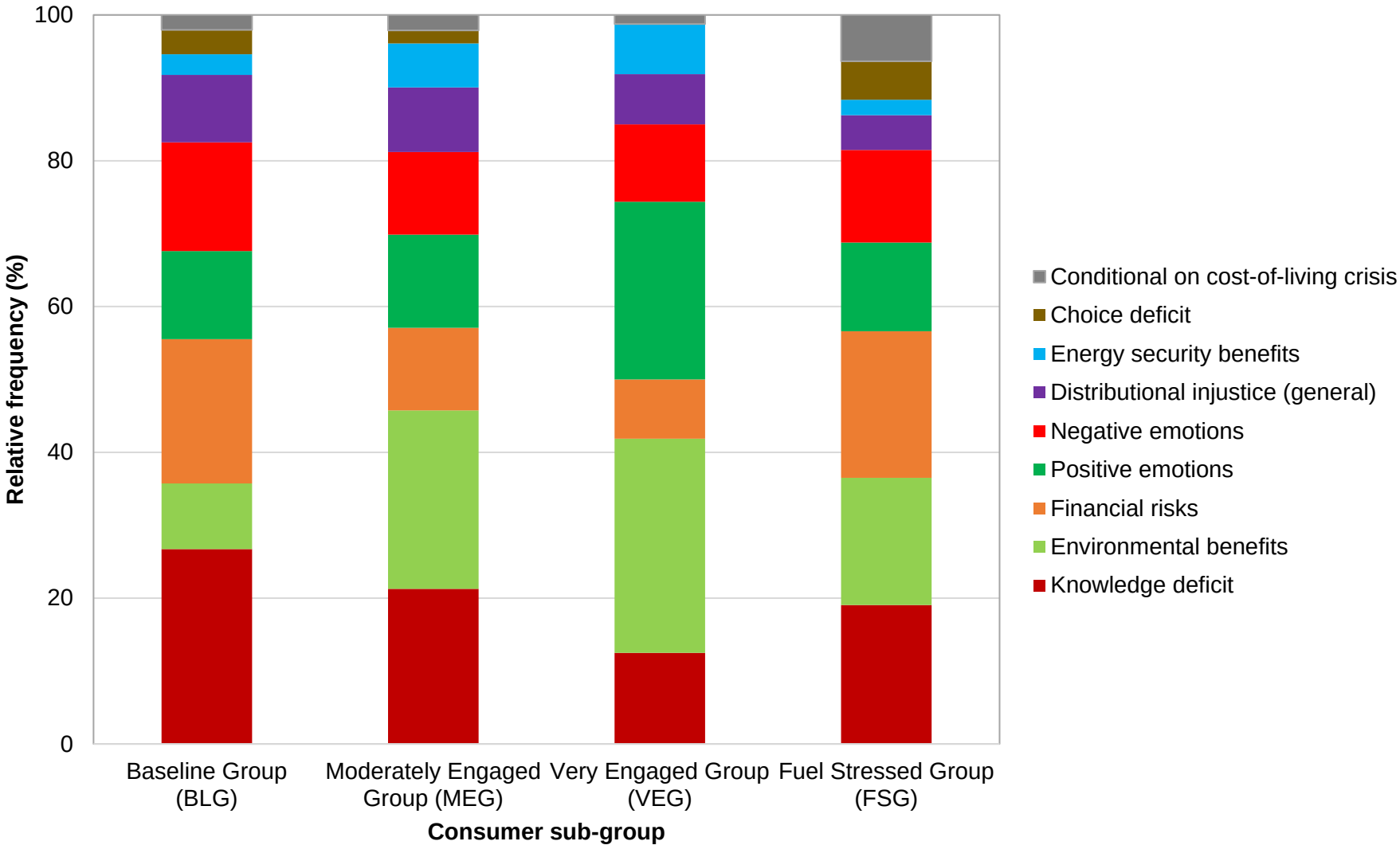


Fig. 3-13. Sub-factors explaining consumer heterogeneity according to relative distribution within sub-groups.

3.4.6.1 Divergence in perceptions of primary sub-factors

Following a Kruskal-Wallis H test, *environmental benefits* (N = 184) emerged as the foremost sub-factor responsible for observed group differences across the sample: H (3, N = 1064) = 32.517, $\rho < 0.001$. The median ranks for each group were as follows: BLG: *Md* = 491; MEG: *Md* = 574; VEG: *Md* = 562; and FSG: *Md* = 523. Consequently, statistically significant differences were observed between three pairwise comparisons: BLG and MEG; BLG and VEG; and FSG and MEG (see Table 3-10).

As the foremost negative sub-factor, *knowledge deficit* (N = 220) accounted for the second highest level of variance across respective sub-groups: H (3, N = 1064) = 29.304, $\rho < 0.001$. Statistically significant differences were observed between the following groups: BLG and VEG, BLG and FSG, MEG and VEG (see Table 3-10). The observed relationship affirms a positive association between hydrogen knowledge and environmental and technology engagement [109,227–229], whereby the VEG had the lowest knowledge deficit (*Md* = 474).

Financial risks (N = 160) associated with the purchasing and running of hydrogen appliances ranked third in terms of observed variance between sub-groups: H (3, N = 1064) = 25.620, $\rho < 0.001$. Notably, concerns were most prevalent along the BLG (*Md* = 563), followed closely by the FSG (*Md* = 548), whereas concerns were less pronounced among the VEG (*Md* = 486), and to a lesser extent, the MEG (*Md* = 514). As reported in see Table 3-10, statistically significant differences are observed between the following groups: BLG and MEG; BLG and VEG; FSG and VEG.

Positive emotions (N = 144) emerged as a significant predictor of consumer heterogeneity at the 10% level: H (3, N = 1064) = 6.666, $\rho = 0.083$. Meanwhile, *negative emotions* (N = 130) proved significant at nearer to the 5% level: H (3, N = 1064) = 7.238, $\rho = 0.065$. Foremost, the VEG expressed the highest proportion of positive emotions (*Md* = 561), followed by the MEG (*Md* = 530), and BLG (*Md* = 527), while the FSG were the least positive (*Md* = 518). Consequently, one pairwise comparison proved significant at the 10% level, namely, between the FSG and VEG ($\rho = 0.096$).

These patterns held partially true when considering negative emotions, which were transmitted foremost by the BLG (*Md* = 550) and least by the VEG (*Md* = 511), whereas the MEG (*Md* = 529) and FSG (*Md* = 527) had a comparable median rank

score. It follows that the BLG and VEG were distinct from one another in terms of negative feelings (ρ = 0.054). Overall, the VEG proved the most positive and least negative consumer segment (see Table 3-10). Thus, the comparative analysis reveals contrasting emotional responses between the VEG and BLG, whereas the MEG and FSG were close to equally balanced in this regard, as illustrated in Fig. 3-12 and Fig. 3-13 (see Appendix M).

Table 3-10. Pairwise comparisons for primary sub-factors of domestic hydrogen acceptance.

		Environmental benefits		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	<0.001*** (0.20)			
VEG	<0.001*** (0.17)	1.000 (0.03)		
FSG	0.359 (0.08)	0.035** (0.12)	0.301 (0.10)	
		Knowledge deficit		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.324 (0.08)			
VEG	<0.001*** (0.22)	0.007*** (0.15)		
FSG	0.009*** (0.13)	1.000 (0.06)	0.399 (0.09)	
		Financial risks		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.008*** (0.13)			
VEG	<0.001*** (0.19)	0.636 (0.07)		
FSG	1.000 (0.04)	0.326 (0.09)	0.005*** (0.16)	
		Positive emotions		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	1.000 (0.01)			
VEG	0.214 (0.09)	0.389 (0.08)		
FSG	1.000 (0.03)	1.000 (0.03)	0.096* (0.12)	
		Negative emotions		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.759 (0.06)			
VEG	0.059* (0.11)	1.000 (0.05)		
FSG	0.765 (0.06)	1.000 (0.00)	1.000 (0.05)	

ρ-values are reported for each comparison, while the effect size given in parentheses.
*** Statistically significant at the 1% level.
** Statistically significant at the 5% level.
* Statistically significant at the 10% level.

3.4.6.2 Divergence in perceptions of secondary sub-factors

Choice deficit (N = 28) ranked fourth when considering observed variance between sub-groups: H (3, N = 1064) = 10.968, ρ = 0.012. As illustrated in Fig. 3-12, consumer heterogeneity was attributed to the VEG (*Md* = 519) making no reference to concerns around a lack of choice related to the hydrogen switchover, whether in terms of the process itself or a lack of agency in choosing one's technology options. By contrast, the FSG registered the highest level of concern within their qualitative answers (*Md* = 546), followed by the BLG (*Md* = 537), and the MEG (*Md* = 528). Consequently, statistically significant differences were observed between the BLG and VEG (ρ = 0.071), and moreover, the FSG and VEG (ρ = 0.016), as reported in Table 3-11.

Two sub-factors related to economic aspects proved significant in shaping group differences, namely, responses *conditional on the cost-of-living crisis* (N = 28), and *energy security benefits* (N = 43), which ranked fifth and ninth, respectively. A Kruskal-Wallis test returned the following result for *conditional on the cost-of-living crisis*: H (3, N = 1064) = 10.342, ρ = 0.016. Consumer heterogeneity was attributable to the FSG having a higher frequency of responses (*Md* = 549) compared to the VEG (*Md* = 524); and to a lesser extent the MEG and BLG (*Md* = 530).

In terms of differences regarding perceptions of *energy security benefits*, the result proved close to significant at the 5% level: H (3, N = 1064) = 7.783, ρ = 0.051. Recognition of hydrogen's potential for improving energy security registered more noticeably among the MEG (*Md* = 544) and VEG (*Md* = 540) in comparison to the BLG (*Md* = 527) and FSG (*Md* = 521). However, as shown in Table 3-11, only one pairwise comparison proved close to significant at the 10% level (MEG–FSG: ρ = 0.102). Overall, the evidence suggests non-technology and environmentally engaged respondents are less likely to acknowledge hydrogen's potential for securing a more resilient energy supply. On the one hand, this could be due to an associated *knowledge deficit*, which may be more pronounced among fuel stressed respondents. Alternatively, it is plausible that a lack of technology and environmental engagement has a diminishing impact on positive economic perceptions.

Table 3-11. Pairwise comparisons for secondary sub-factors of domestic hydrogen acceptance.

		Choice deficit		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	1.000 (0.05)			
VEG	0.071* (0.10)	1.000 (0.06)		
FSG	1.000 (0.04)	0.286 (0.09)	0.016** (0.15)	
		Conditional on cost-of-living-crisis		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	1.000 (0.00)			
VEG	1.000 (0.04)	1.000 (0.04)		
FSG	0.066* (0.11)	0.105 (0.11)	0.017** (0.15)	
		Distributional injustice (in general)		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	1.000 (0.01)			
VEG	0.350 (0.08)	0.750 (0.07)		
FSG	0.101 (0.10)	0.274 (0.09)	1.000 (0.02)	
		Fairness and equity		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.708 (0.06)			
VEG	0.002*** (0.15)	0.218 (0.10)		
FSG	1.000 (0.06)	1.000 (0.00)	0.231 (0.10)	
		Energy security benefits		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.241 (0.08)			
VEG	0.992 (0.06)	1.000 (0.02)		
FSG	1.000 (0.03)	0.102 (0.11)	0.439 (0.09)	

ρ-values are reported for each comparison, while the effect size given in parentheses.
*** Statistically significant at the 1% level.
** Statistically significant at the 5% level.
* Statistically significant at the 10% level.

Finally, in terms of references to equity and fairness, participant statements focused on issues of *distributional injustice* (N = 81) – not specified to related objections regarding the costs of the hydrogen transition – ranked sixth as a predictor of consumer heterogeneity: H (3, N = 1064) = 8.804, ρ = 0.044. Generalised comments on issues of distributional injustice were most pronounced among the BLG (*Md* = 544), followed by the MEG (*Md* = 540), VEG (*Md* = 520), and FSG (*Md* = 515). However, in view of under-representation of the FSG, it is instructive to analyse response patterns in comparison to all aspects of ***fairness and equity*** (N = 221). Accordingly, Fig. 3-14

provides a means for better distilling differences between groups to reflect the interrelated and compounding nature of energy injustice.

Drilling down suggests that distributional injustice is a key concern across all sub-groups. However, it is noteworthy that the FSG flagged general equity issues with a low frequency due to a higher concentration around specific aspects of distributional injustice (see Fig. 3-13 and Fig. 3-14). Foremost, fuel stressed respondents feel the responsibility of paying for the domestic hydrogen transition should rest on the shoulders of government, whereas the MEG attribute stronger levels of accountability to energy companies, especially in view of their sustained profit margins.

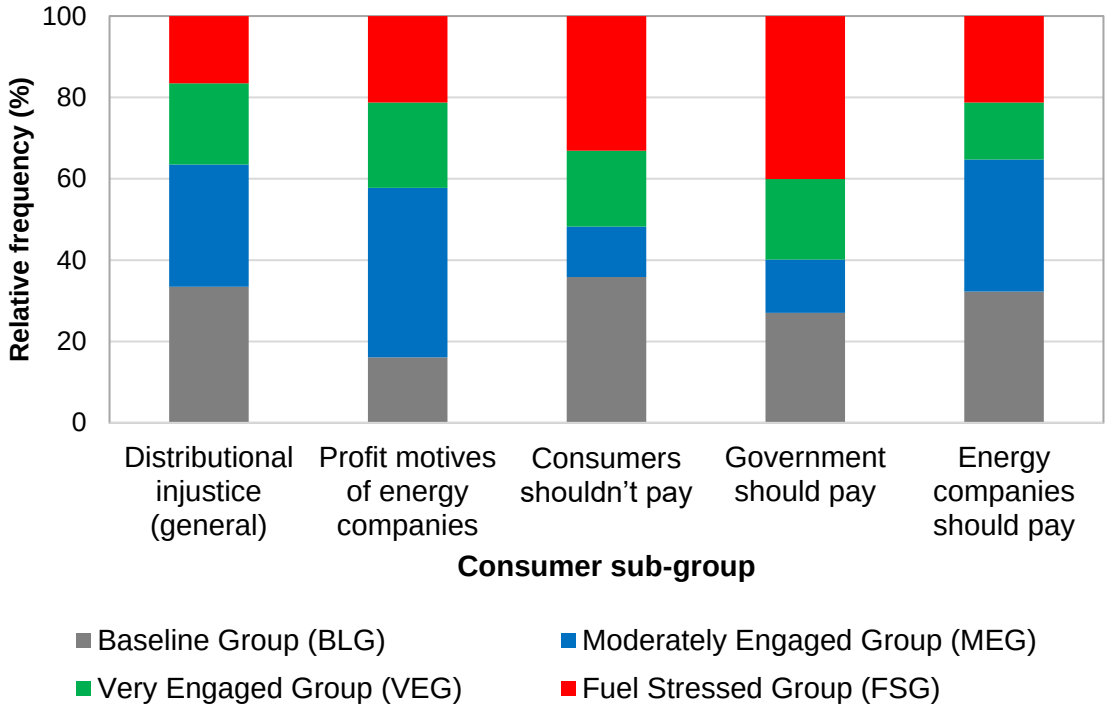


Fig. 3-14. Comparison of distributional injustice sub-factors across consumer sub-groups.

In summary, ***fairness and equity*** ranks ahead of most sub-factors, excluding *environmental benefits*, *knowledge deficit*, and *financial risks*, in predicting consumer heterogeneity, as reflected by the following result: H (3, N = 1064) = 13.363, ρ = 0.004. Concerns related to fairness and equity were least pronounced among the VEG (*Md* = 489) and most prominent among the BLG (*Md* = 558), with the MEG proving marginally less concerned (*Md* = 531) than the FSG (*Md* = 533). Consequently, the disparity between the BLG and VEG proved significant at the 1% level (see Table

3-11). Conceivably, this result may be partially attributed to the VEG having the highest income levels among all sub-groups [121], as further discussed in Appendix M.

3.4.6.3 Summary of statistical findings

Overall, this analysis identifies five primary sub-factors and four secondary sub-factors which predict consumer heterogeneity to varying degrees. As illustrated in Fig. 3-12 and Fig. 3-13, the foremost sub-factors explaining group differences are *environmental benefits*, *knowledge deficit*, and *financial risks*, which are also the top three ranking factors in terms of total references across the sample (see Fig. 3-7). It emerges that environmental, informational, and financial dimensions of domestic hydrogen are fundamental to the emerging contours of social acceptance, while aspects of fairness and equity linked to *energy injustice* are also highly significant. Furthermore, emotional responses reflect underlying heterogeneous attitudes towards hydrogen homes, which may ultimately dictate public sentiment [135].

The results imply that negative emotions may reflect greater divergence in hydrogen perceptions than positive emotions. This is a potentially critical finding since contestation and scepticism have recently dictated the trajectory of domestic hydrogen futures in the UK context [230–232]. Specifically, in July 2023, a planned village trial for Whitby village in Ellesmere Port (Cheshire) was cancelled by the UK Minister for Energy Efficiency and Green Finance (Lord Callanan) [233]. The decision stemmed largely from a pronounced trust deficit and perceived lack of choice among residents, alongside other perceptions of distributional injustice, which culminated in local opposition to hydrogen homes [234–236]. Critically, around 10.3% of the Whitby population experience fuel poverty [237], while the surrounding area of Ellesmere Port ranks within the top 8% most deprived areas in England, according to the 2019 English Indices of Deprivation (IoD) [238]. Consequently, socio-demographic factors may have exacerbated a sense of reluctance among parts of the Whitby village population towards the prospect of trialling hydrogen homes.

3.5 Discussion

This section firstly discusses the implications of sub-factors, following the analysis undertaken in Sections 3.4.2–3.4.6. Thereafter, a further exploration and comparative analysis of core factors is discussed to advance the findings presented in Section 3.2 and Section 3.4.1.

3.5.1 Leveraging opportunities to promote hydrogen acceptance

At present, a pervasive knowledge deficit may undermine the feasibility of securing social acceptance for the domestic hydrogen transition. This threat is amplified in view of the association between consumer scepticism towards hydrogen technologies and a lack of knowledge and awareness [239,240]. However, consumers are also eager to learn more about hydrogen homes (see Section 3.4.3.1), which includes interest in financial aspects of the transition and safety implications (see Table M-3). As a result, deploying hydrogen homes would likely require implementing strategic measures to first raise the underlying awareness of the technology across society.

However, it must be recognised that laypeople often presume that increased knowledge of a topic (e.g. environmental crises) will help inform their decision-making in a certain direction (i.e. pro-environmental behaviour), however, seminal contributions to the literature have often challenged this notion [241]. A significant evidence base highlights the discrepancy between peoples' self-reported knowledge, intentions, and actions; and by proxy their estimation of knowledge as a critical behavioural factor [242]. Studies reflect this discrepancy in associated terms including the 'knowledge-action gap' [243], 'value-action gap' [244,245], 'intention-behaviour gap' [246], and 'attitude-behaviour' gap [247,248]. Furthermore, it has been shown that acquisition of technical knowledge does not necessarily translate into behavioural change in the context of environmental practices [249] such as household energy consumption [243].

Studies investigating the effect of energy literacy on energy conservation are yet to produce systematic evidence of a positive relationship [250,251]. Consequently, Sovacool and Blyth [252] concluded that high levels of energy literacy and awareness may prove incompatible with the decarbonisation agenda in Denmark, while other scholars highlight the influence of cultural differences in determining policies for energy conservation and education [253]. Nevertheless, the extent to which literacy may inform consumer decision-making remains somewhat contested, with several studies identifying knowledge as a necessary but insufficient factor in the environmental context [254], and moreover, in relation to public acceptance for both nuclear power [255] and renewable energy [256].

It follows that increased knowledge, which can be referred to in this context as ‘hydrogen literacy’, may support consumer acceptance, but only when critical factors such as positive emotions (see Fig. 3-7) and perceptions of fairness (see Fig. 3-14) are adequately aligned. As a result, technology acceptance in the context of hydrogen homes is likely to resemble patterns observed across the contemporary consumer behaviour field [257–259]. Thus, consumer knowledge has a role to play in the transition, but should not be considered as a panacea for domestic hydrogen acceptance. As a result, the ranking of *knowledge deficit* and *pro hydrogen information* as the first and sixth sub-factors of domestic hydrogen acceptance (see Fig. 3-7) should be acknowledged within the self-reported context of consumer survey.

Heightened concerns over fairness and equity may precipitate negative emotional reactions such as fear, worry, and scepticism, which would undermine prospects for developing a national hydrogen economy. Foreseeably, such emotions could be partially offset if consumers become more technology and environmentally engaged over time [121], while addressing concerns around financial risks, distributional injustice, a lack of choice, and safety-related risks. Furthermore, consumer responses may shift from resistance or ambivalence, towards tolerance or acceptance [26], if environmental benefits are tangible and effectively communicated [207]. In an ideal scenario, risk factors and perceived costs would gradually be transformed into perceived benefits, or at least neutralised, through public engagement campaigns.

This analysis entails a strong focus on primary sub-factors of domestic hydrogen acceptance, in view of their prevalence (see Fig. 3-7) and influence in predicting consumer heterogeneity (see Fig. 3-12 and Fig. 3-13). However, it should be emphasised that secondary and tertiary sub-factors together account for nearly 43% of the coding results. This weighting reinforces the importance of understanding public perceptions across a range of aspects, especially in view of the strong representation of negative sub-factors beyond the primary level. For example, respondents cited various risks linked to technical and infrastructure challenges (see 3.4.4.2.1), which could otherwise constrain the speed and scale of the domestic hydrogen transition. Additionally, context-specific perspectives and emerging factors such as appliance age and energy security risks (see Section 3.4.5 and Fig. M-3) should also be internalised into decision-making processes.

This study contributes towards understanding consumer heterogeneity in the context of the domestic hydrogen transition; highlighting the relevance of adjusting policy prescriptions and public engagement strategies to meet the needs and expectations of specific consumer segments. Accordingly, domestic hydrogen acceptance would likely be strengthened across society by taking concrete measures to build support among fuel poor communities and fuel stressed households. For example, policies should aim to ensure fuel poor consumers do not incur disproportionate financial risks or marginalisation in terms of technology choice and involvement in the transition. Therefore, definitive action is needed to restore a greater sense of social trust in the government and energy sector [106]. While social acceptance is widely regarded as a precondition to scaling up emerging energy technologies, social trust is critical to supporting the necessary enabling conditions for securing public support.

3.5.2 Strategic targeting of hydrogen acceptance dimensions

While there is clear scope to leverage distinct opportunities for strengthening domestic hydrogen acceptance, it is critical to differentiate between identified areas (i.e. core factors). Drawing a clearer distinction between the potential influence of core factors can help better discern which acceptance dimensions may carry more significance in shaping consumer attitudes and broader public perceptions.

An instructive starting point for devising a more strategic focus – grounded in empirical data – lies with analysing the evidence base reviewed in Section 3.2 (see Table M-5). Among the reviewed materials, four studies [75,77,135,207] engage with at least 10 acceptance factors and can therefore support comparative analysis. Each study critically evaluated and ranked identified acceptance factors according to descriptive or statistical analysis. Additionally, the study of Almaraz et al. [75] presents results from both full counting and binary counting, thereby providing an additional opportunity for extracting comparative insights (see Table M-6 and Table M-7). However, it should be noted that Almaraz et al. [75] reviewed studies on the hydrogen economy (N = 65), while Gordon and colleagues [135] analysed studies on (general) hydrogen acceptance (N = 33), whereas the two remaining articles engaged specifically with domestic hydrogen acceptance [77,207]. Consequently, the comparative analysis is limited to a partial representation of consumer attitudes towards hydrogen homes.

The analytical procedure involved evaluating the sub-factors reported in each study and recoding the results to match the typology employed in Fig. 3-4. In several cases, there was close overlap or direct crossover between the core factors identified in this study and terminology used in other analyses (see Table 3-1, Table M-1 and Table M-5). This similarity reflects the notion that the proposed acceptance typology is strongly grounded in findings from literature review (see Section 3.2). However, this study is the first to identify ***image*** as a core factor of domestic hydrogen acceptance (see Fig. 3-15), relaying the extent to which hydrogen's social representation will likely shape public perceptions [260].

Additionally, it is noteworthy that ***image*** is the only core acceptance factor ranking within the primary group that fails to account for group differences. It follows that, when expressed, a positive social representation of hydrogen may prove relatively homogenous across different parts of the population. However, the controversy surrounding cancelled village trials for hydrogen homes in the North of England [233,261] have contributed towards increasingly negative representations of hydrogen in the UK media [232,262–264]. As a result, there is palpable apprehension regarding the current socio-political legitimacy of prospective hydrogen trials [26]. Foremost, the research community should respond by analysing the role of social representation in shaping attitudes towards hydrogen homes, as reflected by ***image*** as the first ranking core factor when calculated via binary counting (see Fig. 3-6).

Notably, the comparative analysis suggests ***financial*** is predominantly a high ranking or primary factor, as is ***environment***. However, ***fairness and equity*** is a mid-ranking factor, whereas ***technology*** and ***safety*** are typically mid-to-low ranking factors. Nevertheless, across the four reviewed studies [75,77,135,207] it is challenging to extract consistent patterns (see Table 3-12), which likely reflects the different methodologies applied such as systematic literature review [75,135], narrative literature review [77], and structural equation modelling [207].

An additional mode of analysis is to compare the total frequency of core factors identified within the small sample (N = 4) to the results of this study, as shown in Fig. 3-15 (see Table M-7). In some cases, there is close convergence between the literature findings and ranking of core factors presented in Fig. 3-6. Specifically, ***information***, ***environment***, ***safety***, ***logistics***, and ***performance*** have similar levels

of representation. However, to date, ***finance*** and ***affect*** are significantly underexplored within the literature compared to the importance levels reflected in this study. This observation highlights the need to increase research efforts to better understand the financial and emotional dimensions of domestic hydrogen acceptance.

It is further suggested that ***economy***, ***fairness and equity***, and ***social*** are somewhat over-represented in studies to date, when contextualised according to their potential influence in shaping hydrogen perceptions. On the one hand, this result may reflect the fact that only two of the four studies had an explicit focus on hydrogen homes. Evidently, studies engaging with the broader hydrogen economy necessitate a stronger focus on socio-economic aspects [74], while the need to address issues of 'hydrogen justice' is increasingly recognised among the research community. [221,265,266].

Consequently, instances of what may be otherwise be misconceived as research bias can be largely explained and justified. Critically, the main priority should be to address areas of under-representation, as neglecting key acceptance factors in future studies would lead to a degree of stagnation in advancing the international evidence base. By contrast, numerous studies on issues such as hydrogen justice can serve to further enrich the growing evidence base by stimulating new insights.

To close this analysis and discussion, a final synthesis can be offered to advance current levels of understanding among key stakeholders involved in the domestic hydrogen transition, while directing subsequent research efforts to shape future perspectives. Certain core factors such as ***finance*** and ***economy*** share close overlap to the techno-economic dimension, whereas ***technology*** and ***performance*** correspond to the technological dimension, among other examples. An additional recoding procedure condenses the 13 core acceptance factors into eight dimensions which are ranked as follows in view of their composition: (1) ***techno-economic*** (N = 439, 22.7%: *finance*, *economy*, *logistics*); (2) ***social representation*** (N = 333, 17.2%: *image*, *social*); (3) ***emotional*** (N = 262, 13.5%: *affect*); (4) ***psychological*** (N = 260, 13.4%: *information*); (5) ***environmental*** (N = 232, 12.0%: *environment*); (6) ***ethical*** (N =162, 8.4%: *fairness and equity*); (7) ***technological*** (N = 143, 7.4%: *technology*, *performance*); and, (8) ***safety*** (N = 104, 5.4%: *safety*).

If further classified according to the schema presented in Fig. 3-6, it follows that ***techno-economic*** and ***social representation*** compose the primary category, while ***emotional***, ***psychological***, and ***environmental*** comprise the secondary category, with ***ethical***, ***technological***, and ***safety*** constituting the tertiary level of acceptance dimensions. This marks a novel contribution in disseminating the potential influence of drivers of domestic hydrogen acceptance based on extensive qualitative evidence sourced from primary data collection.

Among a range of key insights, the analysis reflects the likelihood that ethical aspects concerning the deployment of hydrogen homes are a comparatively lower priority when faced with more immediate financial risks, which aligns to the findings presented in Table 3-12. It also telling that technological and safety dimensions rank lowest, which may reflect a general expectation that switching to hydrogen boilers and hobs would approximate a close substitute for existing gas appliances [23,207].

This study finds limited evidence that the disruptive impacts of the switchover process are more than a moderate concern or secondary sub-factor (see Section 3.4.4.2.1), which somewhat contradicts the narrative portrayed by Thomas et al. [198], following deliberative workshops carried out in Wales, as well as the findings of Lozano et al. [109] in the Australian context. An explanation for this discrepancy may be the inclusion of a greater number of acceptance (sub-)factors in this analysis, which in turn approximates a more accurate comparative evaluation. However, this analysis aligns with prior findings [77] including the study of Thomas and colleagues [198], by highlighting the extent to which financial risks weigh strongly on the mind of UK households. Critically, financial perceptions reflect the ongoing impacts of the energy crisis [106]. Notably, the current socio-economic environment reflects the emergence of *conditional on the cost-of-living-crisis* as a predictor of consumer heterogeneity, following a higher response rate from fuel stressed respondents.

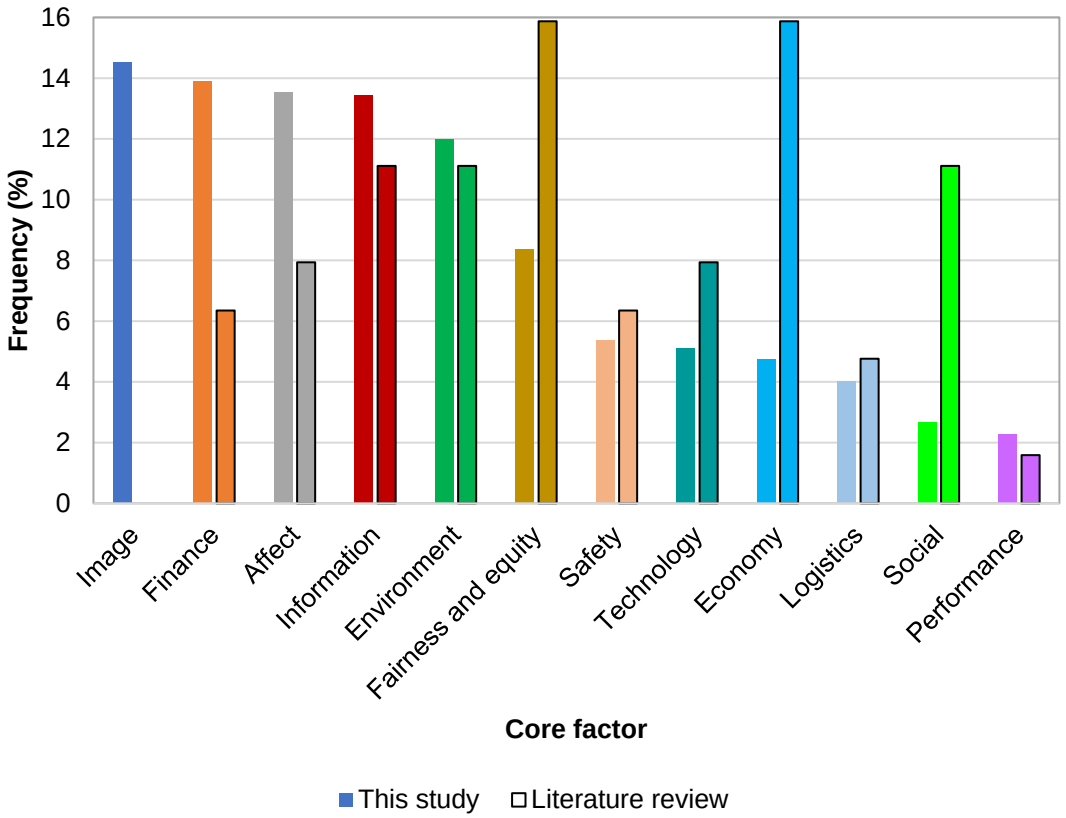


Fig. 3-15. Comparison between core factors of domestic hydrogen acceptance identified in this study and literature review.

Results from this study are presented by the first bars.
Literature review results are distinguished by a dark blue border.
Selected colours represent a single factor to enhance readability.

Table 3-12. Comparative analysis of identified core factors influencing hydrogen acceptance.

Rank	This study (binary counting)	[77][a]	[207][b]	[75] (full counting)	[75] (binary counting)	[135][c]
1	IMG	FIN	SOC, ECON, ENV	INFO, LOG	FIN	ENV
2	FIN	INFO	AFF	FIN	INFO, LOG	SOC, ECON, ENV
3	AFF	LOG	ENV	FIN, F&E	ECON	SOC, ECON, ENV
4	INFO	F&E	F&E	SOC, ECON, ENV	FIN, F&E	F&E
5	ENV	TECH	AFF	ECON	F&E	SFTY
6	F&E	TECH	LOG	F&E, ECON	F&E, ECON	SOC, ECON, ENV
7	SFTY	SFTY	SOC, ECON	F&E	F&E	TECH, PERF
8	TECH	ENV	SFTY	F&E	SOC, ECON, ENV	INFO
9	ECON	F&E	INFO	F&E	SOC, ECON	INFO
10	LOG	F&E	INFO	SOC, ECON	TECH	FIN
11	SOC	F&E		TECH	F&E	AFF
12	PERF	AFF		SFTY	SFTY	AFF
13		ECON				INFO
14		TECH				

Grey = Affect (AFF); Light blue = Economy (ECON); Green = Environment (ENV); Gold = Fairness and Equity (F&E); Orange = Financial (FIN); Blue = Image (IMG); Red = Information (INFO); Pale blue = Logistics (LOG); Mauve = Performance (PERF); Pale orange = Safety (SFTY); Bright green = Social (SOC); Teal = Technology (TECH).

[a] The rank order is derived by qualitative assessment of findings in the literature (N = 17)

[b] The rank order is derived via the effect size (f^2) pf acceptance constructs in a partial least squares structural equation model (N = 1845)

[c] The rank order is derived via frequency of occurrence in reviewed studies (N = 33), which is also the case in Almaraz et al. [75] (N = 65).

3.6 Conclusions

This study bridges a critical research gap by delineating the parameters of domestic hydrogen acceptance in view of salient factors and predictors of consumer heterogeneity. Through mixed-methods analysis, grounded in quantifying qualitative data and exploring statistical findings, the research distinguishes between primary, secondary, and tertiary core factors and sub-factors of domestic hydrogen acceptance. Notably, this study is the first to establish a comprehensive hydrogen acceptance typology in which parameters are clearly defined and supported by qualitative evidence, thereby overcoming the limitations of previous analyses (see Table 3-1).

This research contributes towards understanding consumer perceptions of hydrogen homes, in addition to explaining the degree to which attitudes converge or diverge in relation to critical factors of domestic hydrogen acceptance. Foremost, it has been established that distinct acceptance factors can be empirically measured and further characterised according to their respective influence in shaping consumer attitudes. Based on consumer responses collected between October and December 2022, the analysis shows that factors may range between having a primary, secondary, or tertiary effect on domestic hydrogen acceptance, with statistically significant differences observed between consumer sub-groups at the sub-factor level.

By elucidating the importance of specific drivers and barriers to social acceptance, results from this analysis can help support a more strategic and coordinated response from key stakeholders. Principally, in line with the key findings, stakeholders can seek opportunities to allocate resources towards addressing critical acceptance factors, while adjusting measures to match the expectations of respective consumer segments. In view of the results, several policy and strategy recommendations emerge.

Firstly, information dissemination must adhere to bridging a specific knowledge gap surrounding environmental, financial, and safety implications, among other factors such as appliance performance [23,73,267]. Relatedly, the results affirm the importance of strengthening hydrogen’s image or social representation in the public consciousness, as a tractable commercial technology and long-term sustainable fuel. Consequently, prospects for transitioning homes to hydrogen and advancing the

national hydrogen strategy will hinge firmly on public perceptions of perceived environmental and socio-economic benefits [207]. Foremost, there is an increasing imperative to deliver targeted communication campaigns and demonstration projects, which are grounded in principles of procedural, distributional, and recognition justice [106].

In view of recent events in Ellesmere Port [235], key stakeholders such as gas distribution network operators, alongside central policy makers and local government representatives, must act decisively to restore a greater sense of trust in the country's energy strategy and political process [106]. The government and energy sector should take decisive action to overcome mounting trust deficits, and public concerns over inequality and socio-economic deprivation [106]. Absent of these measures, hopes for hydrogen homes [204] could otherwise be deflated indefinitely and derailed in a way reminiscent to fracking in the UK [268,269]. The imminent risk is that negative imagery associated with hydrogen boilers and hobs could spread or 'spillover' [270] to other parts of the hydrogen economy [5,221]; threatening efforts to decarbonise industrial sectors and transport applications [28,271], which would put a stranglehold on visions for a net-zero society [272].

Although the case of hydrogen homes may appear somewhat isolated, both in technological terms and geographically [26], decisions on domestic hydrogen are likely to have a ripple effect across parts of the national hydrogen economy. Regional events in the UK could also hold potential global implications for technology diffusion and climate change targets. Regardless of broader spillover effects, it is apparent that public perceptions of domestic hydrogen [20,198] and the ensuing discourse on residential decarbonisation [205] will shape ambitions for realising a net-zero society.

While the domestic hydrogen transition remains at an early stage and is currently contested [198,273], findings from this study can enrich the evidence base on consumer attitudes towards residential decarbonisation. The results apply directly to the domestic energy context [25], but also hold critical lessons for other sectors of the economy such as transport [274] and industry [275]; wherein local communities and end-users are set to interact with hydrogen energy systems and associated technologies [73,111,276].

Whether focused on the context of hydrogen homes, or other hydrogen technologies and low-carbon energy sources, this study transmits the benefits of distilling consumer acceptance and heterogeneity through an empirically-grounded typology. Accordingly, the proposed acceptance typology presents significant opportunities for exploration in subsequent research. This opportunity can be leveraged by integrating further insights from survey data, sourced from both the UK and abroad, in parallel to employing complementary research methods [277] such as deliberative workshops [198] and focus groups [276].

Critically, researchers should further unpack the potential relationship between social trust and consumer choice in shaping hydrogen acceptance, which can be advanced through a mixed-methods research design [110,278]. Checking the validity of the statistical findings should be taken forward as a focal point of future research, which can target a more in-depth understanding of perceptions of fairness, equity, and justice in relation to hydrogen homes (see Fig. 3-14).

Additionally, follow-up studies should further examine secondary and tertiary core factors and associated sub-factors of domestic hydrogen acceptance. This focus will contribute towards validating observations from the UK context as retrieved during the winter of 2022. The aim should be to facilitate a longitudinal evidence base, as achieved to an extent by Martin et al. [195] in the Australian context, and Yap and McLellan [279] in Japan. In parallel, there are increasing opportunities for cross-country analysis, which should be leveraged to support previous studies on hydrogen fuel cells in the European context [193,280].

This study set out to advance a preliminary typology of domestic hydrogen acceptance, which will inevitably change as consumer attitudes and preferences evolve over time, as conceptualised within Rogers' five stages of the innovation-decision process [281]. As hydrogen homes currently remain at the pre-deployment or formative phase of technology diffusion [282], the presented typology reflects the interplay between two stages; the 'knowledge stage' where consumers become aware of the technology, and the 'persuasion stage' where initial attitudes are formed in view of perceived risks, costs, benefits, and associated factors, ahead of the 'decision stage' (i.e. adoption or rejection) [283].

Consequently, the prominence of ***information*** as a primary core factor is likely to diminish over time, as its respective constituent sub-factors – *knowledge deficit* and *pro hydrogen information* – may contribute less significantly to domestic hydrogen acceptance. To an extent, this pattern is observed within the data, since ***image***, ***finance***, and ***affect*** emerged as more prominent core factors than ***information*** when applying binary counting to the dataset (see Fig. 3-6). In addition to corroborating whether ***information*** may be an inflated core factor due to potential response bias associated with the established 'knowledge-action gap' [243] (see Section 3.5.1), follow-up studies can illuminate how other acceptance factors and the dynamics of consumer heterogeneity may change over time.

Moving forward, the presented typology can help fine-tune engagement in domestic hydrogen acceptance, which may prove fruitful, if not critical, to supporting policy ambitions for accelerating residential decarbonisation and developing a national hydrogen economy. Given the importance of public engagement to the trajectory of net-zero pathways, acceptance typologies should be advanced as a critical mechanism for pre-empting social resistance and enacting a 'just' hydrogen economy.

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4 COUPLING GREEN HYDROGEN PRODUCTION TO COMMUNITY BENEFITS: A PATHWAY TO SOCIAL ACCEPTANCE?

An earlier version of Chapter 4 (Coupling green hydrogen production to community benefits: A pathway to social acceptance?) has been published in Energy Research & Social Science: https://doi.org/10.1016/j.erss.2024.103437

Highlights

- Environmental and socio-economic benefits underpin domestic hydrogen acceptance
- The UK public favour green hydrogen over blue hydrogen production
- Positive emotions towards the hydrogen transition outweigh negative emotions
- Prospects for hydrogen homes are undermined by a deficit in public trust
- Motivates the advancement of PLS-SEM in hydrogen acceptance studies

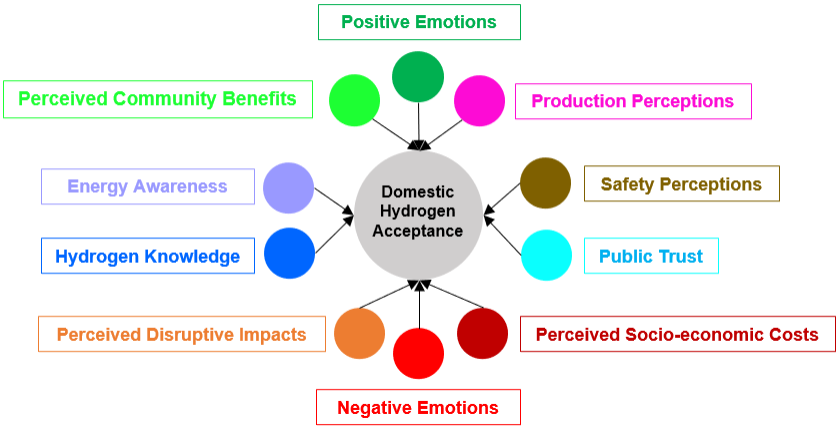
Keywords

Domestic hydrogen acceptance; Green hydrogen; Energy transitions; Hydrogen economy; Partial least squares structural equation modelling; Importance-performance map analysis

Abstract

Hydrogen energy technologies are forecasted to play a critical supporting role in global decarbonisation efforts, as reflected by the growth of national hydrogen energy strategies in recent years. Notably, the UK government published its Hydrogen Strategy in August 2021 to support decarbonisation targets and energy security ambitions. While establishing techno-economic feasibility for hydrogen energy systems is a prerequisite of the prospective transition, social acceptability is also needed to support visions for the 'hydrogen economy'. However, to date, societal factors are yet to be embedded into policy prescriptions. Securing social acceptance is especially critical in the context of 'hydrogen homes', which entails replacing natural gas boilers and hobs with low-carbon hydrogen appliances. Reflecting the nascency of hydrogen heating and cooking technologies, the dynamics of social acceptance are yet to be explored in a comprehensive way. Similarly, public perceptions of the hydrogen economy and emerging national strategies remain poorly understood. Given the paucity of conceptual and empirical insights, this study develops an integrated acceptance framework and tests its predictive power using partial least squares structural equation modelling. Results highlight the importance of risk perceptions, trust dynamics, and emotions in shaping consumer perceptions. Foremost, prospects for deploying hydrogen homes at scale may rest with coupling renewable-based hydrogen production to local environmental and socio-economic benefits. Policy prescriptions should embed societal factors into the technological pursuit of large-scale, sustainable energy solutions to support socially acceptable transition pathways.

Graphical abstract



4.1 Introduction

Researchers have examined the feasibility of hydrogen-based energy systems since the 1970s [1,2], with industrial and academic interest in applications such as long-term storage of electricity in power systems [3,4] and low-carbon steel production [5,6] increasing within recent years. Foreseeably, harnessing the potential of hydrogen for decarbonisation purposes [7–9] may help confront the 'super wicked problem' of climate change [10]. Notably, Levin et al. [11] specify four parameters to the climate challenge: (1) time is running out; (2) those who create the problem are intertwined in solving it; (3) a lack of central authority and weak global commitment; and (4), a tendency towards irrational discounting that inhibits more immediate action.[1]

The emergence of hydrogen energy technologies (HETs) in the global policy arena follows several decades of scientific interest towards promoting a transformative and sustainable 'hydrogen economy' [2,12–14]. As described by the International Energy Agency (IEA), seizing this opportunity is now widely recognised as imperative to the low-carbon transition [15], with prospects for supporting a more secure, resilient, and cost-effective energy system [16,17], through multi-sectoral development across the global hydrogen economy [7,18,19].

The potential role of hydrogen in combatting climate change is best reflected by the recent uptake of national (hydrogen) strategies [19–21], as described in Appendix N (see Fig. N-1). Of foremost relevance to this study, the UK government set an initial hydrogen production target of 5GW for 2030, following the release of its national Hydrogen Strategy in August 2021 [22]. However, following Russia's invasion of Ukraine, which has dramatically altered the global energy landscape,[2] the target has been doubled to 10GW[3] [23]. Specifically, the UK government suggests hydrogen could account for 20–35% of UK final energy consumption (~250–460TWh) by 2050, in support of reaching the country's net-zero target [24]. Relatedly, Chapman et al.

[1] Jakimowicz [351] also discusses the energy transition as super wicked problem, when considered as part of a prosumer capitalism paradigm.
[2] In the aftermath of COVID-19 [170] and following the macro-economic shock of the ongoing Russia-Ukraine conflict [171,415], the geo-technological, economic, and political stakes of the global hydrogen economy are especially high for European nations [416], as further detailed in Appendix N.
[3] Of which at least 5GW should be sourced from electrolytic (i.e. 'green') hydrogen. Additionally, the Scottish Hydrogen Action Plan (December 2022) [132] aims for at least 25GW of installed renewable and low-carbon hydrogen production by 2045.

[25] suggest hydrogen could account for 2% of global energy consumption under a scenario where 30% hydrogen is blended into city gas.

The UK also has growing ambitions to leverage the potential of cross-border trade opportunities with Europe [26]; reflected by plans to develop a 2000 km hydrogen network to link major UK industrial clusters with the European hydrogen backbone (EHB) [27,28].[4] These developments could help realise the UK government's vision to increase low-carbon hydrogen demand to 38TWh by 2030, with the industrial sector accounting for up to 21 TWh, before growing overall demand to 55–165 TWh by 2035.

Embedded in its Energy Security Bill, the UK government is supporting a portfolio of low-carbon technologies, through legislation committed to enacting "a secure, clean and affordable" long-term energy future [29]. Critically, the landmark Bill includes legislative measures to support a village-scale trial for hydrogen homes in the North of England [30], ahead of a strategic decision on the role of domestic hydrogen in 2026 [22]. However, several socio-technical barriers to the transition persist [19,31] including the need to secure social acceptance, which is configured by interactions across socio-political, market, community, attitudinal, and behavioural dimensions [32,33].

Energy transition scholars posit that social acceptance [34,35] involves "multi-dimensional, dynamic processes" [36] which are "complex, multi-level, and polycentric" in nature [37]. Accordingly, social acceptance can be characterised as a multi-actor process [38] operating across the macro-, meso- and micro-levels [36]. Synthesising recent contributions to the literature [33,39–41], this study contends that consumer attitudes towards domestic hydrogen will involve a specific interplay between different acceptance dimensions and factors. On the one hand, deploying hydrogen homes will involve the 'human factor' in technology adoption [42],[5] which links strongly to attitudinal and behavioural acceptance at the household level [32,33]. At the same time, broader factors such as social trust and community benefits will influence public perceptions [41], as witnessed in the case of onshore wind siting [43].[6]

[4] The EHB envisions close to 40,000 km of hydrogen pipeline infrastructure across 21 countries by 2040 to support the decarbonisation agenda [26,27].
[5] Specifically, Lutzenhiser [42] discuss residential energy consumption as operating through macro-social and micro-behavioural processes.
[6] For example, Fournis and Fortin [43] describe cross-scalar interactions for deploying onshore wind farms, which span macro-economic, meso-political, and micro-social levels.

Although conceptual understanding of domestic hydrogen acceptance has emerged [33,44], empirical studies are yet to examine which constructs may prove the most salient predictors of consumer attitudes [39]. Bridging the gap between social acceptance theories [33,45,46] and recent contributions to the hydrogen futures literature [39,47], this research sets out to advance theoretical and empirical understanding of domestic hydrogen acceptance. The study employs partial least squares structural equation modelling (PLS-SEM) [48,49] to develop and test the predictive power of a conceptual framework, hereafter referred to as the Domestic Hydrogen Acceptance Model (DHAM).

The DHAM is employed to determine the extent to which cognitive processes, social capital, environmental attitude, risk perceptions, cost-benefit appraisal, and affective response influence consumer acceptance and adoption intention for hydrogen home appliances. Accordingly, this study develops a “theory-driven, data-grounded model” to advance understanding on sustainable energy acceptance [50]. In addition to advancing conceptual understanding, this analysis presents policy makers and key stakeholders with critical insights for realising national hydrogen economies and the wider energy transition.

Following this introduction, Section 4.2 provides an overview of theoretical and methodological developments in hydrogen acceptance studies, while Section 4.3 develops a series of hypotheses based on literature review findings. Next, Section 4.4 presents the conceptual framework, while Section 4.5 describes the methodology. Section 4.6 reports and discusses the results of the DHAM, while Section 4.7 concludes by highlighting the theoretical, empirical, and practical implications of the study.

4.2 Theoretical and methodological developments in hydrogen acceptance studies

Reviewing the early hydrogen futures literature [51,52], Ricci et al. [53] concluded that conceptualisations of hydrogen energy technology (HET) acceptance overlook several “key aspects and dimensions by which people make sense of new technologies and consume them.” Furthermore, survey studies on HET acceptance have been critiqued for lacking a whole-systems perspective, whereby focus on a specific end-use technology (i.e. hydrogen fuel cell vehicles and fuelling stations) neglects wider

interactions across the hydrogen economy and energy system [53]. Subsequently, Roche et al. [54] called for acceptance studies to integrate a whole-systems perspective of HETs, while also advocating for expansion beyond frameworks rooted in social psychology,[7] risk perceptions, and economics.

More recently, through a narrative review of 27 quantitative studies conducted since 2005, Scovell [39] reinforced the need to expand HET acceptance beyond narrow analyses on transport applications. Emphasising this point, Emodi et al. [47] carried out a systematic literature review, wherein only five studies (N = 43) concentrated on residential hydrogen. Such contributions highlight the limitations of prior survey studies, advocating for deeper exploration into the salient constructs of HET acceptance and interactions between acceptance dimensions.

Crucially, Scovell [39] laid the groundwork for systematically examining the relationship between socio-psychological factors and HET acceptance. Foremost, each of the 27 studies included in his review [39] operationalised the conceptual tenets presented in the Sustainable Energy Acceptance Technology (SETA)[8] and its predecessors [44] such as the Technology Acceptance Model (TAM) [55][9] and the Unified theory of Acceptance and Use of Technology (UTAUT) [56].[10] Notably, Venkatesh and colleagues [57] advanced a second iteration of the UTAUT (i.e. UTAUT2), before proposing a multi-level framework for analysing technology acceptance in the consumer context [58]. In parallel, researchers in the field of energy acceptance have adopted and adapted the TAM and UTAUT to examine a range of technologies [59–62], including smart meters and associated technologies for smart homes [63,64].

As summarised by Scovell [39], the SETA framework synthesises well-established theories of human behaviour, namely the Theory of Planned Behaviour (TPB) [65], the Norm Activation Model (NAM) [66], and theories focused on risk perceptions [67] and related emotional responses to technology [68]. Through the lens of the SETA, the following constructs were identified as salient factors of hydrogen acceptance:

[7] i.e. models for attitude formation and behavioural intention.
[8] Also referred to in the literature as the Comprehensive Technology Acceptance Framework (CTAF).
[9] The TAM was developed by Fred Davis in the mid-1980s [418], integrating constructs from the Theory of Reasoned Action (TRA) [419], as well as Rogers' Diffusion of Innovation (DoI) theory [420], to evaluate user acceptance of computer technologies in the organisational setting [421].
[10] In 2001, Venkatesh et al. [56] subsumed a range of critical acceptance constructs from eight established models to develop the UTAUT framework.

knowledge (objective and subjective); awareness; experience and engagement; perceived effects (risks, costs, and benefits); public trust; fairness; affect (i.e. emotional response); problem perception; personal norm; and socio-demographic factors [39].

In the Australian context, Lozano et al. [69] drew on the SETA to develop a conceptual approach based on three dimensions of social acceptance (socio-political, market, and community); combining a range of variables including household characteristics and energy use, innovator category, stakeholder trust, climate change beliefs, and environmental identity. While seemingly comprehensive, the adapted version of the SETA, as described above, failed to define constructs such as climate change beliefs and environmental identity to a specific acceptance dimension, while conflating risk and safety under market variables [69]. This lack of demarcation undermines theoretical rigour and weakens the validity of empirical results, since no specific hypotheses were formulated, while variables were miscategorised [69].

While Lozano et al. [69] developed important comparative insights regarding public perceptions of domestic hydrogen and hydrogen for export in Australia, the analysis was limited to first generation multivariate regression analysis, which has significant limitations compared to SEM [70] (see Section 4.5.2). Despite the availability of advanced statistical methods for overcoming prior research limitations in quantitative studies, as specified by Scovell [39] and evidenced in Lozano et al. [69], recent contributions to the hydrogen acceptance literature have largely failed to leverage the benefits of second-generation techniques such as SEM [70,71].

Specifically, in 2022 Yap and McLellan [72] evaluated attitudes of Japanese society towards the hydrogen economy using an online survey.[11] The conceptual framework [72] drew on the earlier qualitative model of Schulte et al. [73] – albeit with a wider sense of coverage on knowledge, values, and related perceptions towards a future hydrogen-based economy[12] – but the analysis was limited to descriptive statistics. While this research decision may be partially attributed to the comparative focus, the

[11] The authors conducted a nationally representative online survey (N = 2880) in March 2022 [72], which was compared to results from 2015 (N = 3133) [97].
[12] i.e. self-reported and objective knowledge and values towards the environment, energy security, safety, economic efficiency, and energy justice.

analysis also reflects a persistent failure to operationalise acceptance constructs within hydrogen survey studies [39].

Researchers such as Emmerich et al. [74] and Scovell [39] acknowledge how individual, local, and general acceptance levels will shape prospects for developing national hydrogen economies [70]. More concretely, Gordon et al. [33] identify a range of social, political, economic, financial, contextual, ethical, socio-psychological, and socio-cultural factors [33]. This inherent multi-dimensionality reflects findings from other energy acceptance studies wherein a range of latent variables explain consumer attitudes [50,75,76]. This research internalises these dynamics by integrating a range of acceptance constructs to reflect the interplay between socio-political, community, market, and household acceptance dimensions [33,41], which are reflected in the hypotheses developed in Section 4.3 and subsequent conceptual framework (see Section 4.4).

Overall, this assessment of recent contributions to the literature supports the recommendation of Scovell [39] to extend theoretical and empirical outputs on hydrogen perceptions, wherein a viable starting point is to examine how "different methods of production, storage and transport may interact to influence acceptance at different levels." In response, analytical studies should reflect hydrogen's unique status, as a technology with cross-cutting upstream and downstream impacts [39], which hold significant implications for shaping public perceptions and individual attitudes [32]. Critically, researchers should leverage the advantages of more rigorous quantitative methods such as PLS-SEM to advance comprehensive insights on domestic hydrogen acceptance and adoption intention (see Section 4.5.2).

4.3 Hypotheses development

This section reviews a range of literature materials to develop hypotheses for each of the exogenous constructs which compose the proposed model. Semantically, 'exploratory' research may suggest an explicit focus on hypothesis generation using qualitative methods [70,77]. Additionally, hypothesis testing may infer the need for an exclusively explanatory focus [78]. However, an exploratory approach also entails conducting quantitative research to test emerging hypotheses [70,77] under conditions of limited conceptual knowledge and scarce empirical [49].

In response, PLS-SEM provides a flexible (i.e. non-parametric) approach to support hypothesis testing and statistical conclusions via an exploratory, 'causal-predictive' research paradigm [49]. This research paradigm complements the 'causal-explanatory', retrospective focus of CB-SEM [79], as further discussed in Section 4.5.2. As a result, PLS-SEM has proved the method of choice for social scientists when conducting exploratory modelling and hypothesis testing across a range of disciplines [80–82] including sustainable energy transitions research [83–87]. In total, ten hypotheses are proposed to test the antecedents of domestic hydrogen acceptance and determine the predictive capabilities of the DHAM (see Section 4.6.5).

4.3.1 Awareness and knowledge

Following Roger's Diffusion of Innovation (DoI) Theory [88], knowledge initiates the grounds for persuasion, decision-making, implementation and finally, confirmation, which together reflect a five-stage process of technology adoption and evaluation (i.e. 'innovation-decision'). Knowledge can be conceptualised as a heterogeneous concept made up of at least three components: 'awareness-knowledge', 'how-to knowledge', and 'principles knowledge' [88].[13]

Currently, hydrogen appliances for domestic heating and cooking [89] remain at the formative phase [90] or pre-deployment stage of technology diffusion [91,92]. Consequently, few consumers are yet to trial hydrogen home appliances [93,94]. Thus, little information is known about consumer attitudes towards potential adoption [32], as well as underlying social acceptance [33,69]. Given the nascency of the low-carbon hydrogen industry, this study reports survey responses regarding awareness and subjective (i.e. self-rated) knowledge [95].[14] Specifically, respondents were asked: "How much do you know about hydrogen fuel?"

Foremost, hydrogen awareness and knowledge levels remain low across most countries [96–98] including the UK [99]. Notably, awareness of hydrogen boilers is significantly lower than other low-carbon heating technologies such as solar thermal panels and heat pumps [100], underscoring the peripheral status of domestic

[13] Awareness-knowledge is a proxy for familiarity with a given technology, which is a prerequisite for subsequent knowledge types and technology adoption [421,422]. Thus, awareness influences the scope for socio-psychological and attitudinal responses towards a given technology [211].
[14] The rationale applied is that subjective knowledge (hereafter 'knowledge') can also be considered as a close proxy for awareness-knowledge [88] or perceived familiarity [422], and may ultimately reflect one's potential interest and engagement level [299,421].

hydrogen [101,102]. Nevertheless, consumer attitudes towards HETs often side towards the positive end of the acceptance spectrum [33,103], while knowledge and awareness of renewable energy typically increases support for hydrogen [104]. This positive association is particularly prevalent among educated males [105–107].

Furthermore, in the German context, a recent study argued that knowledge has a positive impact on the adoption intention of both HFCVs and electric vehicles throughout all stages of the innovation-decision process [108]. Additionally, Bharadwaj et al. [109] found that a combined information package given to Australian respondents raised support for domestic hydrogen and hydrogen for export use by 9% and 11%. Given the current evidence base, this study tests develops the following hypotheses to test whether a significant positive relationship is observed in relation to cognitive processes and domestic hydrogen acceptance (see Table N-1).

H1: Awareness (AWR) of low-carbon energy technologies including hydrogen home appliances has a significant positive influence on the social acceptance of domestic hydrogen.

H2: Knowledge (KNW) about hydrogen fuel has a significant positive influence on the social acceptance of domestic hydrogen.

4.3.2 Public trust

Public trust is a multi-dimensional construct, which reflects how society perceives the competence and integrity levels of given stakeholders [110–112]. Public trust has important implications for community acceptance [34], with evidence from China (Jiangsu Province) highlighting how community backing for industrial agglomeration (i.e. synergies between local industries and manufacturers) can promote support for the hydrogen economy [113].[15] Trust dynamics have been shown to heavily shape hydrogen acceptance at the individual, community, and national level [114], reinforcing the multi-dimensional focus embedded in the ‘five dimensions of domestic hydrogen acceptance framework’ [33].

[15] By no coincidence, the German Government’s National Innovation Programme for Hydrogen and Fuel Cell Technology [423] was supported by academic projects resonating with the notion of public trust, namely, HyTrust (2009–2013) and HyTrustPlus (2014–2016).

Following such projects, extant evidence supports the notion that public trust is a key dimension of domestic hydrogen acceptance [32,93,115], especially given the community and individual impacts of converting the gas grid [39,116]. Crucially, a deficit in public trust [41] may undermine socio-political acceptance [34], thereby aggravating the potential for social friction towards the hydrogen economy [117].

UK consumers have comparatively high levels of trust in evidence on hydrogen provided by the Health and Safety Executive (HSE), whereas the media are regarded as untrustworthy [115]. Interestingly, another study reported neutral levels of trust in the national regulator, the Office of Gas and Electricity Markets (Ofgem) [118]. Furthermore, the public may have relatively high confidence regarding the ability of government and industry to carry out requisite safety and environmental checks [115,119], but question the commitment of the same entities towards enacting procedural and distributional justice [41,120].

The public may also look towards renewable energy producers to steer the hydrogen transition in the right direction [69,121] by ensuring the green credentials of national hydrogen strategies come to fruition [122]. Relatedly, financial institutions are actively involved in supporting the transition to a low-carbon economy [123], although significant financial and policy de-risking is needed to dimmish green investment risks [124]. Accounting for these dynamics, this study measures public trust in the following actors and stakeholders: the media, Ofgem, Gas Distributions Network Operators (GDNOs), renewable energy producers, and financial institutions (see Table N-1).

In summary, public trust can drive support for residential decarbonisation [125], positively shape attitudes towards climate change and environmental policies [126,127], and act as a mechanism for raising social capital and improving economic efficiency [128]. In response, the following hypothesis is formulated to test the effect of public trust on domestic hydrogen acceptance (see Appendix N).

H3: Public Trust (PT) in key actors and stakeholders has a positive influence on the social acceptance of domestic hydrogen.

4.3.3 Production perceptions

The relative merits of different hydrogen production technologies have been discussed in view of techno-economic factors [31,129] including the levelised cost of CO_2 mitigation [130]. In parallel, prospects for respective hydrogen production pathways

will hinge on public perceptions [121,131]. For example, Parkison et al. [130] and Griffiths et al. [7] note the likely challenge associated with nuclear-based hydrogen production in view of negative safety perceptions and lack of public support.

The UK Hydrogen Strategy envisions a 'twin-track' production approach reliant on steam methane reformation (SMR) and carbon capture and storage (CCS), alongside "electrolytic hydrogen predominantly powered by renewables" [22]. More ambitious targets for hydrogen production since the outbreak of the Russia-Ukraine conflict [23,132] (see Appendix N) signal the importance of hydrogen production pathways as a key pillar of national energy policy, with key implications for social acceptance [131].

The 'hydrogen futures' literature [51,133] demonstrates a stronger degree of public support for renewable energy-based production [99,121,134], compared to a blue hydrogen production (i.e. SMR with CCS[16]) [106,119]. The Welsh public expressed a preference for hydrogen production generated by wind farms as opposed to fossil fuel feedstocks [107]. Similarly, Norwegian citizens showed support for coupling onshore wind and hydrogen production [135], alongside a clear preference for green hydrogen over alternative options [121].

However, data collected by Yap and McLellan [72] highlighted two divergent perspectives among Japanese respondents: 55% preferred cheaper 'grey' hydrogen production (i.e. fossil-fuel based without CCS), whereas 45% were in favour of green hydrogen, given its environmental benefits and despite its higher costs. Interestingly, findings from online focus groups conducted in the UK suggest a lack of clarity regarding the premise of the government's twin-track approach, with environmentally engaged respondents expressing higher degrees of scepticism [131].

It follows that the 'colour labels' [136,137] of hydrogen production methods communicate environmental cues to citizens, thereby shaping social acceptance [121]. Accounting for the foreseeable influence of hydrogen production pathways, and by proxy environmental attitudes towards these decisions, the following hypothesis is proposed in view of the twin-track approach (see Table N-1), wherein the effect may prove positive or negative according to the sample composition:

[16] Notably, CCS presents its own set of unique challenges related to social acceptance [182,424,425].

H4: Production Perceptions (PP) will significantly influence the social acceptance of domestic hydrogen.

4.3.4 Safety perceptions

Blending hydrogen into the natural gas grid [138,139] may present a tangible measure towards realising national hydrogen economies [140,141]. However, this pathway and related infrastructure investments such as hydrogen-dedicated pipelines [26] will incur new safety challenges [142,143]. Potential safety risks will be heightened when considering hydrogen for domestic use [31] as opposed to industrial applications [7].

Notably, examining acceptance for HFSs in Japan, Ono and Tsunemi [144] found that risk perception factors related to safety incidents were stronger predictors of consumer acceptance than psychological and socio-demographic variables. Prior research has also shown that hydrogen's distinct physical and chemical characteristics may elicit consumer concerns [89], and moreover, feelings of fear and dread [144,145].

Both UK [93,146] and Australian survey respondents [69,147] expressed concerns over hydrogen's colourless flame and lack of smell, as well as its combustibility and flammability [32]. Interestingly, female respondents in Australia reported higher concerns than males in view of hydrogen's potentially disruptive impacts to the lived experience of cooking and associated risk factors [106]. By contrast, an earlier study in the Netherlands observed stronger perceptions of explosiveness among males [105]. Similarly, in the case of green hydrogen production, Welsh respondents raised concerns over explosive risks [146].

It follows that safety perceptions may play an important role in shaping hydrogen acceptance, especially during the early stage of the transition where risks are likely to be most elevated and uncertain. Nevertheless, online survey (N = 700) and paper-based survey respondents (N = 102) from the North of England perceived potential safety benefits from a switch to domestic hydrogen [102].[17] Focus group results also suggest that citizens feel relatively reassured about hydrogen, provided adequate safety tests are carried out [93]. However, the safety risks of hydrogen cooking are perceived to be higher than for hydrogen heating [89,148].

[17] 17.3% and 34.7% answered positively while 13.9% and 7.9% answered negatively, although neutral (i.e. no impact) was the prevailing response (i.e. 68.9% and 57.4%).

In view of the notion that risk perceptions may stem largely from media coverage [149,150], and given the current lack of consensus on safety perceptions within the literature, this study focuses on a comparative assessment between hydrogen and natural gas (see Table N-1), without specifying the nature of this relationship [151]. Accordingly, the following hypothesis is developed to advance the evidence base, while seeking to mitigate perception bias:

H5: Safety Perceptions (SP) will significantly influence the social acceptance of domestic hydrogen.

4.3.5 Perceived disruptive impacts

It is widely accepted that converting the gas grid to hydrogen will engender a certain level of safety challenges [152,153], which may translate to perceived risks in the eyes of the public [89,94]. To date, most of the literature has concentrated on risk perceptions concerning safety aspects [73,154,155]. Safety-related concerns can be classified as 'hard' risks concerning technical hazards related to pipelines [156] and appliances [157], wherein the dangers are severe and carry direct implications for human wellbeing [158].

By contrast, 'soft' risks are less harmful and easier to mitigate [44,158]; revolving around potential short-term disruption risks which households may incur during the hydrogen switchover [93]. These non-hazardous risks [158] can be measured according to levels of consumer concern or worry [159]. For example, one nationally representative online study conducted in the UK (N = 1027) found that 20% of respondents were cautious about adopting domestic hydrogen and concerned about disruptive impacts [160].

Risk perceptions in this sense will revolve around potential disruptive impacts, which may include "infrastructural changes and operational activities at street level, as well as temporary disconnection from the gas grid and engineering activities within properties" [33]. Focus group participants from one UK study specified a general tolerance for disconnection from the gas grid for a maximum of four days [93], which has been corroborated by subsequent findings [41]. However, thresholds for the duration of disconnection may prove context specific and depend on energy vulnerabilities [41,93].

Elsewhere, focus group participants have described disruptive risks in terms of higher levels of traffic and noise [41], which links to the perceived burden of appliance installation (i.e. hydrogen boilers and hobs) [93]. Critically, to enable conditions for a large-scale conversion program [161], consumers must perceive disruption-related risks to be tolerable [33]. Accordingly, the following hypothesis is explored to account for prospective short-term disruptions (see Table N-1), which if not adequately mitigated could impede the prospective transition to hydrogen homes:

H6: The Perceived Disruptive Impacts (PDI) of the hydrogen switchover will negatively influence the social acceptance of domestic hydrogen.

4.3.6 Perceived socio-economic costs

The perceived socio-economic costs of domestic hydrogen can be measured at different scales [33] including the macro- or national level [36]. However, this construct remains underexplored by researchers [39,162], with limited theoretical or empirical investigation beyond the boundaries of safety and environmental impacts [39], which is also reflected in the wider technology acceptance literature [163]. In most instances, discussions on cost-related aspects of hydrogen are restricted to the individual unit of analysis regarding financial impacts to consumers [102,164,165], and sometimes extended to the community level by considering negative effects to host communities [166].

While the existing evidence base in sparse, some notable results have been reported in the literature. Foremost, Scott and Powells [102] found that most survey respondents in the North of England anticipated neutral or positive macro-economic impacts from the domestic hydrogen transition. However, it should be noted that the distribution of responses was skewed towards neutral perceptions (i.e. ‘no impact on the economy’) [102]. Furthermore, it should be borne in mind that the survey in question [102] was conducted before a string of unpredictable and destabilising economic events [167,168], following the COVID-19 pandemic [169,170] and Russo-Ukrainian War [171,172], as described in Appendix N. Consequently, the current political and economic landscape remains volatile [173,174], with concurrent events exacerbating fuel poverty pressures in the UK [175,176].

Drawing from previous research [32,44], this study focuses on the macro-economic risks of the domestic hydrogen transition, which will influence both socio-political and

market acceptance. Two related areas of interest receive attention, namely, the perceived impacts of the hydrogen switchover on energy insecurity and fuel poverty (see Table N-1). These areas also serve as proxies to inform consumer perceptions regarding the cost-competitiveness and affordability of domestic hydrogen. Reflecting these measurements items, the following hypothesis is tested:

H7: The Perceived Socio-economic Costs (PSC) of transitioning to hydrogen homes will negatively influence the social acceptance of domestic hydrogen.

4.3.7 Perceived community benefits

Perceived risks and social costs are often critical to energy acceptance, especially when concerning a hazardous technology such as nuclear power [177,178], as well as emerging energy technologies [179]. Nevertheless, recent evidence suggests that perceived benefits is the most influential predictor of social acceptance; not only for renewable electricity generation [180] and low-carbon heating technologies [181], but also CCS [182] and even nuclear power [183,184].

As with perceived risks and social costs, perceived benefits can be evaluated across different dimensions [185,186]. For example, Damette et al. [187] investigated consumer perceptions in relation to hydrogen's benefits for French households, the electricity grid, and environment. Notably, survey respondents in both Australia [106] and the UK [119] express support for implementing a local green hydrogen economy aligned to community benefits; identified as job security, energy security, and environmental improvements [188], which may help reinvigorate industrial communities [41,119]. Furthermore, support for hydrogen in the North of England also increased when participants were briefed about the fuel's potential environmental benefits [115], while Bentsen et al. [121] reported perceived environmental benefits as a key predictor of hydrogen acceptance in Norway.

Given the importance of local economic, social, and environmental benefits to energy technology acceptance [189], these parameters are likely to shape public opinion and consumer attitudes towards domestic hydrogen [32]. While awareness regarding the benefits of hydrogen remains relatively low [39,190], unpacking this tripartite dimension (see Table N-1) may reveal key inferences regarding hydrogen's perceived contribution towards tackling the energy trilemma [191] and safeguarding against

energy injustice [192]. Consequently, the following hypothesis is examined to account for the remaining dimension of ‘perceived effects’ [39,193]:

H8: The Perceived Community Benefits (PCB) of transitioning to hydrogen homes will positively influence the social acceptance of domestic hydrogen.

4.3.8 Positive and negative emotions

Socio-psychological and attitudinal drivers find further expression in the form of emotional responses [194,195], which is reflected in the academic literature via the application of various psychological evaluation metrics [163,196,197] such as the Technology Affect Scale (TAS) [198]. Mirroring findings in the information technology acceptance literature [199,200], emotions play an instrumental role in shaping energy acceptance [201,202]. The affective (i.e. emotional) dimension of renewable energy acceptance has attracted increasing attention from researchers [202–205] when examining the broader potential for a sustainable energy transition [195,206].

Qualitative findings from this dataset cite a wide range of emotional responses, with optimism, hopefulness, happiness, excitement, and eagerness among the most prevalent responses, while concern, confusion, fear, nervousness, and scepticism dominated negative reactions [103,120]. Negative emotions may prove particularly relevant for risk perceptions related to safety aspects [207,208]; foremost when consumers associate hydrogen with explosiveness, danger, and catastrophe vis-à-vis past incidents [107,149,207,209]. Emotions such as fear and dread [144,145,210] could shape the emerging contours of hydrogen acceptance, as witnessed historically with controversial energy technologies such as nuclear power [211]. Additionally, feelings of unfamiliarity concerning hydrogen may evoke anxiety, concern, and scepticism [54,102].

Conversely, positive emotions such as pride, joy, and gratitude may prove emergent among local hydrogen communities [210,212], reinforcing the imperative to examine the emotional dimensions of energy acceptance through a holistic lens [210]. It follows that positive and negative emotions should be evaluated as interacting, yet distinct dimensions of hydrogen acceptance [44]. As a result, this study investigates the following hypotheses in parallel (see Table N-1):

H9: Positive Emotions (PE) towards hydrogen homes will positively influence the social acceptance of domestic hydrogen.

H10: Negative Emotions (NE) towards hydrogen homes will negatively influence the social acceptance of domestic hydrogen.

4.3.9 Acceptance and adoption dynamics

By accounting for the mechanisms through which constructs influence each other [213], mediation analysis provides a critical tool for examining the complexity of human behaviour within a statistical model [214]. Thus, mediation analysis supports testing the causal pathways proposed within a theoretical framework [215,216], which can be operationalised via PLS-SEM [217–219] to examine whether "a mediator variable to some extent absorbs the effect of an exogenous on an endogenous construct in the PLS path model" [220].

Following guidelines in the literature, PLS-SEM practitioners can explore test whether full mediation, complementary partial mediation, competitive partial mediation, or no mediation is detected within the structural model [217,221]. The efficacy of employing mediation analysis is strongly reflected in prior research engaging with energy acceptance [222,223] including studies focused on hydrogen technologies [74,208,224].

Notably, seminal frameworks such as TPB [225] and one of its prominent successors, the TAM [55], posit that behavioural intention mediates the relationship between attitude and behaviour [226]. Accordingly, numerous studies have tested the significance of this relationship across a diverse range of contexts, such as health care [227], artificial intelligence [228], information systems [229], smart energy technology [230], e-services [231] and e-learning [232,233].

Similarly, scholars have explored the mediating role of attitude in predicting behavioural intention, which is also reflected in the TAM.[18] Notably, in the context of sustainable development, Ignacio et al. [234] employed a combined technology acceptance model and theory of planned behaviour (C-TAM-TPB)[19] framework to examine the relationship between attitude towards an integrated water system project and behavioural intention in the Philippines, while Ahmed et al. [235] adopted a similar

[18] Perceived usefulness mediates the relationship between perceived ease of use and attitude.
[19] The C-TAM-TPB was developed by Taylor and Todd [426].

approach to study the factors influencing willingness to participate in sustainable water resources management in Malaysia.

Utilising a decomposed theory of planned behaviour (DTPB)[20] Moons and De Pelsmacker [236] observed that a positive attitude towards the electric car has a significant and positive effect on adoption intention in the Netherlands ($\beta = 0.189$, $p < 0.001$), while Ali et al. [237] reported a positive relationship between consumer attitude and intention to purchase solar PV in Pakistan based on DTPB ($\beta = 0.504$, $p < 0.001$) [237]. Employing an extended UTAUT model, Yang et al. [238] found that attitude towards the use of renewable energy positively predicts behavioural intention among Ghanians ($\beta = 0.227$, $p = 0.016$).

Based on analysis of UK focus group data (N = 58), it was shown that consumers are relatively willing to adopt either a hydrogen boiler ($M = 3.62$) or a hydrogen hob ($M = 3.56$) [148]. Furthermore, support was highest for switching to a hydrogen home ($M = 4.14$), as measured on a five-point Likert scale. Explanatory factors for these results were associated primarily with perceived technology benefits [148], in addition to perceived environmental benefits [131]. In response, this study follows suit and explores the acceptance and adoption dynamics of domestic hydrogen acceptance, which is reflected by firstly testing the direct relationship vis-à-vis social acceptance (i.e. attitude) and adoption intention (i.e. willingness to adopt domestic hydrogen before 2030):

H11: Domestic Hydrogen Acceptance (ACPT) will positively influence Willingness to Adopt Domestic Hydrogen (WTA)

Finally, to extend the analysis, additional hypotheses are tested to explore whether domestic hydrogen acceptance significantly mediates the relationship between each exogenous construct and willingness to adopt domestic hydrogen before 2030 (see Table 4-1).

[20] i.e. decomposing the three main antecedents of behavioural intention posited in the TPB into a set of salient beliefs based on the Diffusion of Innovation (DoI) theory and the Technology Acceptance Model (TAM).

Table 4-1. Hypothesis 12 in the Domestic Hydrogen Acceptance Model.

Hypothesis	Mediating role of Domestic Hydrogen Acceptance (ACPT)
H12a	• ACPT positively mediates the relationship between Awareness (AWR) and Willingness to Adopt Domestic Hydrogen (WTA)
H12b	• ACPT positively mediates the relationship between Knowledge (KNW) and Willingness to Adopt Domestic Hydrogen (WTA)
H12c	• ACPT positively mediates the relationship between Public Trust (PT) and Willingness to Adopt Domestic Hydrogen (WTA)
H12d	• ACPT significantly mediates the relationship between Production Perceptions (PP) and Willingness to Adopt Domestic Hydrogen (WTA)
H12e	• ACPT significantly mediates the relationship between Safety Perceptions (SP) and Willingness to Adopt Domestic Hydrogen (WTA)
H12f	• ACPT negatively mediates the relationship between Perceived Disruptive Impacts (SP) and Willingness to Adopt Domestic Hydrogen (WTA)
H12g	• ACPT negatively mediates the relationship between Perceived Socio-economic Costs (PSC) and Willingness to Adopt Domestic Hydrogen (WTA)
H12h	• ACPT negatively mediates the relationship between Perceived Community Benefits (PCB) and Willingness to Adopt Domestic Hydrogen (WTA)
H12i	• ACPT positively mediates the relationship between Positive Emotions (PE) and Willingness to Adopt Domestic Hydrogen (WTA)
H12j	• ACPT negatively mediates the relationship between Negative Emotions (NE) and Willingness to Adopt Domestic Hydrogen (WTA)

4.4 Conceptual framework

The hypotheses generated in Section 4.3 and associated constructs provide the foundations for advancing a conceptual framework of domestic hydrogen acceptance,[21] which subsumes six specific dimensions as illustrated in Fig. 4-1: cognitive processes, social capital, environmental attitude, risk perceptions, cost-benefit appraisal, and affective response. Through this approach, the study engages with multiple acceptance dimensions, as opposed to a more limited set of psychological parameters [39,69] and attitudinal factors [89,102] featuring in prior studies. While each exogenous construct can be classified as a socio-psychological factor under a traditional technology acceptance framework lens [46,69], the demarcation of each aspect characterises the multi-dimensional nature of the DHAM.

As foundational drivers of attitudes and behaviours [239], awareness and knowledge represent key **cognitive processes** which shape domestic hydrogen acceptance [74], corresponding to H1 and H2 in the proposed model [74]. By contrast, public trust

[21] Brosch et al. [194] demonstrated the increased explanatory power of behavioural models which integrate appraisal-emotion constructs to predict energy-related decision-making at the micro-scale.

develops via social and cognitive processes [240,241]; enabling individuals to form expectations about scenarios and relationships [242] to better evaluate new social settings and choices [241]. Moreover, trust is a critical aspect of **social capital**, which may encourage community acceptance and cohesion, alongside local economic development [243], in support of deploying and scaling up hydrogen homes [31], as explored via H3.

As described, production perceptions can be conceptualised as a proxy for **environmental attitudes**, since UK households may distinguish between support levels for renewable-based and non-renewable based hydrogen production pathways [131], which motivates H4. Although hydrogen production pathways entail important consequences for energy security and other macro-economic factors such as job creation [31,166], the environmental focus typically pervades the public discourse. Specifically, the climate change credentials of blue hydrogen remain highly contested by the scientific community [244,245], while national hydrogen strategies have also been criticised for lacking green commitments, characterised by a "scale first and clean later" ethos [122].

At the level of **risk perceptions**, safety-related impacts and disruptive impacts can be linked to 'hard' and 'soft' risks, respectively [44]. Hard risks correspond to hazards involving damage to infrastructure (i.e. pipeline-related incidents and gas leakage) or end-user accidents (e.g. fire event triggered by a hydrogen cooker), which pose a threat to the environment and compromise human safety [156,158], as explored in H5. By contrast, soft risks are associated with concerns and worries over non-hazardous events [158], such as street-level disruption and other short-term impacts incurred during the hydrogen conversion process [41,93], which are focused on in H6.

Researchers typically focus on the perceived benefits of domestic energy technologies when conducting quantitative studies, while perceived costs are often overlooked [44]. This pattern holds true in the hydrogen acceptance literature [39], although the disparity between assessing these two constructs is somewhat less pronounced [44].

In response, this study subsumes perceived socio-economic costs and perceived community benefits [246,247] under the dimension of **cost-benefit appraisal** [248].[22]

As a result, this framing integrates measures of both socio-political and community acceptance [33] vis-à-vis both negative (i.e. perceived socio-economic costs) and positive implications (i.e. perceived community benefits) of hydrogen homes, which are tested in H7 and H8 respectively. In doing so, this analysis also provides a means for directly comparing public perceptions across the macro- and meso-level.[23]

Lastly, socio-psychological and attitudinal drivers find further expression in the form of **affective response** [194,195], which motivates H9 and H10. Critically, intuitive feelings will influence social acceptance when information remains relatively limited or without a clear consensus, and risk-benefit judgments cannot be arrived to easily [38], which is the case for an emerging technology such as domestic hydrogen. Accordingly, emotional responses to the domestic hydrogen transition may reflect underlying cognitive processes, social and cognitive interactions, environmental attitudes, risk perceptions, and related cost-benefit appraisals, leading to the conceptual framework illustrated in Fig. 4-1.

Lastly, Fig. 4-1 extends the focus by incorporating the hypothesised path between acceptance and adoption intention (H11), which is represented in this study in terms of willingness to adopt domestic hydrogen appliances and a hydrogen home before 2030 (see Section 4.6.1). Accordingly, the final path reflects the premise of the unified theory of domestic hydrogen acceptance [44], which posits a positive relationship between acceptance and willingness to adopt domestic hydrogen, which predicts realised adoption (i.e. purchasing of hydrogen appliances). Furthermore, the DHAM operationalises most of constructs composing the unified theory, excluding objective knowledge, technological perceptions, financial perceptions, and rational thought [44].

[22] The underlying logic is that consumer attitudes towards perceived socio-economic costs at the macro-level (i.e. fuel poverty and energy security impacts) and perceived community benefits (i.e. economic, social, and environmental) will contribute towards a cost-benefit analysis of domestic hydrogen.
[23] A more robust representation would be afforded by including a third measure of perceived costs, namely, (perceived) negative environmental impacts. The survey instrument employed for this measure (PC3) failed to load on the construct, as further discussed in Section 4.7.2.

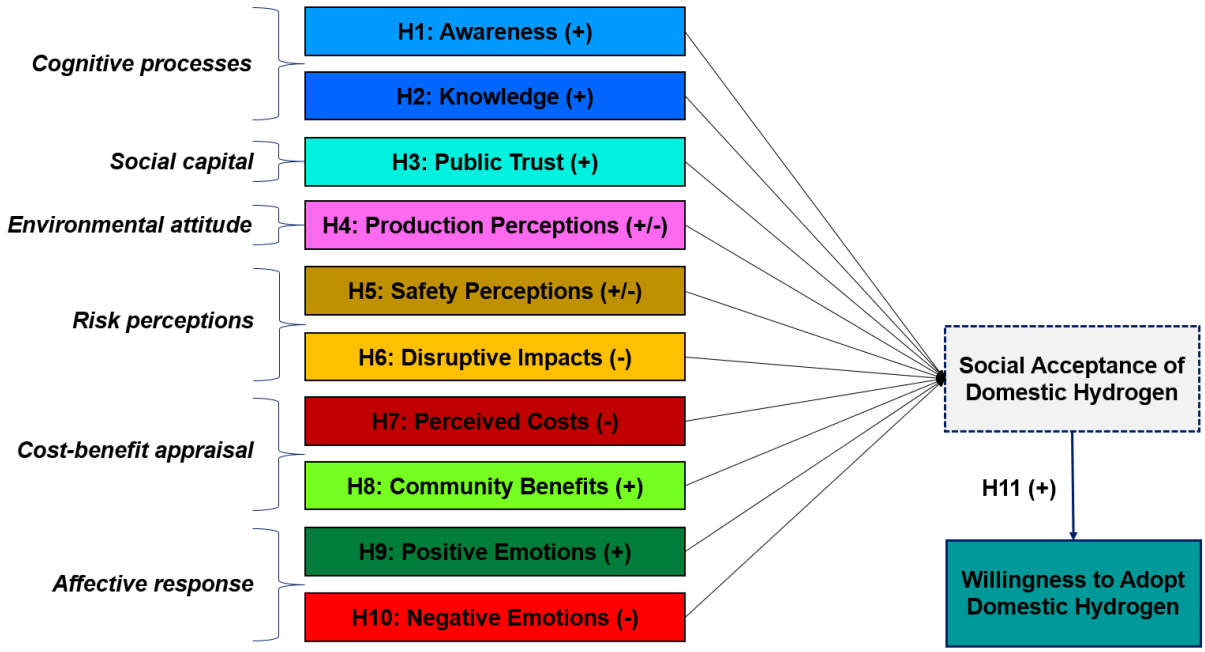


Fig. 4-1. Conceptual framework for examining the acceptance and adoption dynamics of domestic hydrogen.

4.5 Material and methods

4.5.1 Survey design and data collection

This quantitative study employed a web-based survey to collect data on consumer attitudes towards domestic hydrogen in the UK. The survey design was derived through literature review [31–33] and qualitative results from online focus groups [41,131,148]. Questionnaire items were further developed following inputs from hydrogen experts and social scientists working in the energy transitions field. After programming the survey in Qualtrics [249], content and face validity were established through a series of internal piloting rounds. Following an iterative process of survey development which spanned several months, the final questionnaire was deployed by a market research company.[24] Table N-1 provides details of the questionnaire items, answer scales, and literature which informed the survey design.

To help offset survey bias, in addition to minimising drop-out rate due to potential disinterest or fatigue [250,251],[25] a series of information provision materials were included [252].[26] Specifically, participants were provided with information on hydrogen

[24] The survey ran from October 6th to December 23rd, 2022, and was monitored daily by the lead author.
[25] Responses were excluded when deemed unsuitable due a fast completion time (i.e. less than 8 minutes).
[26] The reader can also refer directly to Appendix H for these details.

production methods in the context of the twin-track strategy, hydrogen-related activities in the UK context, and specific details concerning hydrogen boilers and hobs. The selection was based on the use of information provision materials in prior research [147,148,160,253] and informed by recent policy documents [22,23]. Factual and inherently neutral information was selected to support the analysis, as opposed to testing the effects of positive or negative framing [105,254], or scenarios [72,109], which can support the future research agenda (see Section 4.7.2. Nevertheless, the introduction of targeted and objective information has an inevitable influence on respondents' subjective views about hydrogen [69], which could not be directly examined due to the lack of a control group.

The sample is composed of four specific consumer segments (see Fig. N-2), which serves three key functions: (1) ensuring a spectrum of consumer profiles are represented in the sample through inclusion of participants with different levels of technology knowledge and interest, environmental engagement, and socio-economic status (i.e. fuel stressed and non-fuel stressed respondents); (2) increasing national representativeness through this design by directly accounting for the increasing prevalence of fuel poverty pressures in the UK [175,255]; and (3) facilitating opportunities for multigroup analysis (MGA) which has been leveraged in follow-up work [256];

The study was strengthened by implementing a series of measures (i.e. filters and quotas) to approximate a broadly nationally representative sample (see Table N-2-Table N-4). As demonstrated in other research fields such as psychology [257], epidemiology [258], and health services research [259], national representativeness enables clearer estimation of country wide patterns to support generalisable conclusions. Importantly, domestic hydrogen acceptance studies conducted in the UK [115] and Australia [69] have adhered to representing the national population, which is also the aim of this research.[27]

Importantly, this study engages exclusively with existing users of gas boilers and hobs. Furthermore, two additional filters were employed to support the objective of engaging with respondents more likely to be actively involved with a prospective transition to

[27] Specifically, quotas were applied for the following socio-demographic variables: age, gender, housing tenure, housing type and location.

hydrogen homes, or other low-carbon domestic energy technologies: (1) at least moderate involvement in decision-making around the purchase of their heating and cooking appliances; and (2) at least moderate importance attributed to being able to choose these appliances.[28] Notably, the research design supported a valuable opportunity to compare safety perceptions of natural gas and hydrogen for deeper contextual understanding (see Section 4.3.4). Overall, a broadly national representative survey sample was secured (N = 1845), albeit with room for improvement around variables such as age and housing tenure in subsequent studies (see Table N-2).

4.5.2 Structural equation modelling: a second-generation statistical technique

Structural equation modelling (SEM) has a rich and well-documented history [260–262], characterised as a second-generation (2G) statistical technique which is superior to first-generation (1G) techniques for modelling complex causal relationships between latent and observed variables [70,263]. Larsson et al. [264] distinguish regression as engaged with predictive analysis irrespective of causal mechanisms, whereas SEM, through its path modelling approach, is rooted in hypotheses about causal processes:

> "Path modelling is the application of statistical modelling to datasets with the objective of testing and explaining causal hypotheses about theoretical measurement models and structural paths" [77].

In a standard regression model, each equation implies "a statistical relationship based on a conditional expected value."[29] By contrast, SEM implies a 'functional relationship' which is expressed through a corresponding conceptual model, path diagram, and mathematical equations [265]. Put differently, within a SEM, each equation represents a causal link as opposed to an empirical association [266], enabling researchers to examine the causal networks underlying real-world relationships in a more comprehensive way compared to correlation-based models [267].

Accordingly, SEM offers several advantages compared to multivariate regression analysis [268]: supporting theory development through simultaneous testing of

[28] Measured using a five-point Likert scale where the moderate response represented the mid-point.
[29] i.e. each equation within a regression model represents "the conditional mean of a dependent variable as a function of explanatory variables" [263]. Alternatively, Larsson et al. [264] describe regression "as specifying a conditional mean of the outcome based on the predictors."

complex relationships (i.e. measurement and structural models);[30] incorporating measurement error and unexplained variance in the modelling parameters; and ability to link micro- and macro-perspectives of complex phenomenon [267,269]. Compared to 1G techniques, SEM supports greater statistical power [270], higher levels of flexibility (i.e. methodological versatility) [264], ability to test *a priori* hypotheses about causal relationships [264,271], alongside "big-picture, model-based reasoning," whereby relationships between variables are conceptualised as part of an overarching explanatory system processes [264].

4.5.2.1 Approaches to structural equation modelling: CB-SEM and PLS-SEM

CB-SEM and PLS-SEM present complementary, yet distinctive, statistical approaches for estimating parameters of theoretical models [272,273]; diverging in terms of measurement philosophies, estimation procedures, and statistical outcomes [274], as summarised in Table 4-2. The application of PLS-SEM in the social sciences has grown exponentially within the last two decades [77], with scholars increasingly disseminating the predictive benefits of the method to the research community [79,275,276]. Nevertheless, selecting the most suitable SEM approach remains of a focal point of academic debate [80,277], emphasising the need for clear research justification.

As a confirmatory technique, CB-SEM determines whether the hypothesised model fits the observed sample data [77,272,278]. With a focus on model fit and stronger data requirements, CB-SEM is the optimal approach for testing an established and concise theoretical model such as the TPB [279,280]. Thus, researchers may adopt CB-SEM for purposes of theory confirmation [80,281], as applied by Gölz & Wedderhoff [241] when examining onshore wind acceptance in Germany.

CB-SEM follows a maximum likelihood (ML) estimation procedure [282], treating constructs as common factors to explain the covariation between associated indicators [281]. The common factor approach splits total variance into common, unique, and error variance but only uses common variance for estimating the model [283,284]. Thus, residual variance is excluded as measurement error and the focus is on estimating the proportion of common variance explained [284]. As a result, the CB-

[30] 1G statistical techniques require separate analyses to perform validity and reliability tests, which lack a direct relationship to formal hypothesis testing and as a result cannot provide overall fit indices [427].

SEM approach is more prone to metrological uncertainty,[31] which may compromise the validity of the measurement model [283].

In response, the CB-SEM approach may motivate researchers to reduce the number of indicators per construct to increase model fit [273], which has adverse consequences on metrological uncertainty and associated validity [283]. CB-SEM is also subject to factor (score) indeterminacy, since there are infinite sets of latent variable scores that can fit the model to the same extent [70,283]. Therefore, correlations between a common factor and variables external to the factor model become indeterminate, which renders CB-SEM ill-suited for purposes of prediction [70,283].

Overcoming this limitation and bridging the gap between explanation and prediction [288],[32] PLS-SEM produces a unique (i.e. determinate) score for each composite per observation following calculation of indicator weights and loadings, which serve as proxies for the latent constructs [283]. These proxies serve as inputs for executing ordinary least squares (OLS) regression[33] to minimise the error terms (i.e. residual variance) of each endogenous construct in the model [283]. Consequently, PLS-SEM employs a composite-based measurement philosophy; reflecting the notion that latent constructs can be estimated by linearly combining indicators for each construct [283,289].[34] Notably, the composite-based approach supports handling of more complex data compared to CB-SEM [289].

Thus, as a variance-based approach [272], PLS-SEM estimates path coefficients to maximise the explained variance (R^2) of a target construct [283] within a conceptually-grounded path model [290], whereas CB-SEM is limited to explaining the covariation between indicators in the measurement and structural models. Unlike CB-SEM, PLS adopts the logic the entirety of an indicators' variance is relevant for estimating path models [283]. Guenther and colleagues [284] emphasise this distinction as a motivating reason to utilise PLS-SEM, since residual variance may contribute towards

[31] i.e. the dispersion of measurement values that can be explained by the object or concept under examination [283].
[32] PLS-SEM can test a model's predictive capabilities by drawing on out-of-sample tests, but is also suitable for explanatory modelling as supported by in-sample predictive tests [288,428].
[33] OLS minimises the sum of the squared differences between the observed and predicted values of the dependent variable [77].
[34] i.e. PLS-SEM obtains parameter estimates via repeated least squares regression with a single dependent variable [289].

theoretical or empirical meaning due to interaction effects between indicators and constructs.

Table 4-2. Comparison of PLS-SEM and CB-SEM.

Criteria	PLS-SEM	CB-SEM
Method focus	• Prediction-oriented	• Parameter-oriented
Method approach	• Variance-based	• Covariance-based
Method paradigm	• Causal-predictive: employs the coefficient of determination (R^2) to estimate the proportion of total variance explained	• Causal-explanatory: employs the coefficient of determination (R^2) to estimate the proportion of common variance explained
Method assumptions	• Soft-modelling approach with flexibility: predictor specification (non-parametric)	• Rigorous assumptions: multivariate normal distribution (parametric)
Statistical objective	• Maximising the variance explained in a target construct by incorporating common, specific, and error variance into the modelling parameters	• Estimates model parameters that minimise the differences between the observed sample covariance matrix (calculated before the analysis) and the covariance matrix estimated after the revised theoretical model is confirmed
Parameter estimates	• Consistent as indicators and sample size increase (i.e. consistency at large)	• Consistent
Latent variable scores	• Explicit since a single latent variable score is always produced for each composite per observation	• Indeterminate since an infinite number of different sets of latent variable scores can potentially fit the model
Epistemic relationship between a latent variable and its measures	• Supports formative or reflective mode	• Supports reflective indicators typically
Implications	• Optimised for predictive accuracy	• Optimised for parameter accuracy
Model complexity	• Large complexity, e.g. up to 100 constructs and 1000 indicators	• Small to moderate complexity (e.g. less 30-40 indicators)
Sample size recommendation	• Power analysis based on the portion of the model with the largest number of predictors. Typically, the minimum number of cases range from 30 to 100 cases	• Power analysis on specified model. Typically, a minimum number of observations range from 200 to 800.

Source: Authors' design based on [70,285–287].

When extending frameworks such as the TPB [291–293] or modelling complexity via an integrated technology acceptance model (TAM) [294–296], researchers can

employ PLS-SEM for purposes of theory development [292]. Accordingly, PLS-SEM is recommended in situations of high complexity where limited theory formation has been established [80,297], as reflected in the case of emerging hydrogen energy technologies [165,224,298,299]. Nevertheless, it should also be noted that PLS-SEM is suitable for conducting confirmatory research [49,287].

In summary, SEM practitioners such as Henseler [272] and Hair et al. [283] characterise PLS-SEM as a 'causal-predictive' paradigm with the goal of testing a model's predictive power based on theory and logic, whereas CB-SEM follows a 'causal-explanatory' paradigm predicated on theory confirmation and model fit. As a result, PLS-SEM bridges the gap between CB-SEM and exclusively predictive methods [288] such as machine learning and artificial neural networks [300–303]. As a result, PLS-SEM was leveraged to examine the acceptance and adoption dynamics of domestic hydrogen through an exploratory and comparative approach, with a focus on maximising the model's predictive capabilities (see Section 4.6.5).

4.5.2.2 Application of PLS-SEM in SmartPLS 4.0

Using SmartPLS 4.0 software [304], the two-stage approach was applied to analyse and interpret the survey data, firstly assessing the measurement model and secondly, evaluating the structural model. Beforehand, several measures were required to justify the use of PLS-SEM [305], such as a valid research design and sufficient sample size [270], which were checked using model model-specific estimates [306]. Employing G*Power software (see Fig. N-3), the proposed model can demonstrate small effect sizes of 0.02 at a 95% significance level ($\rho < 0.05$) for the specified sample (N = 1845). Secondly, skewness and kurtosis tests were conducted to assess normality [49,307], which confirmed all values were within the preferred threshold of +/-1 (see SN7). Thirdly, common method bias (CMB) was ruled out, since Harman's single factor test [308] returned an overall variance of 27.34%, well below the threshold of 50% (see Table N-5). Overall, the preliminary assessment confirmed the integrity of the data and the suitability of using PLS-SEM.

4.6 Results and discussion

This section reports and discusses the results in four stages. Firstly, Section 4.6.1 reports descriptive findings for the constructs operationalised in the DHAM, as measured using two respective Likert scales in the online survey (see Table N-1). In

doing so, the first sub-section frames the PLS-SEM analysis and hypotheses results against observations at the indicator level. Next, 4.6.2 proceeds by assessing the measurement model. Thereafter, Section 4.6.3 assesses the structural model; as supported by including an IMPA in Section 4.6.4. Section 4.6.5 reports the in-sample and out-of-sample predictive power of the DHAM. Finally, Section 4.6.6 concludes by discussing the links between acceptance dimensions and constructs.

4.6.1 Descriptive statistics

The analysis of descriptive statistics highlights several findings, which hold important implications for the configuration of domestic hydrogen acceptance (see and Fig. 4-2 and Fig. 4-3). Firstly, in relation to the cognitive dimension, this study finds that awareness and subjective knowledge of hydrogen remain low (see Table 4-3), which is consistent with recent findings in the literature [96,121]. For example, based on data collected in the Spring of 2022 (N = 4372), the UK government found awareness of hydrogen fuel (*M* = 2.44, *SD* = 1.11), and of its potential future uses to reduce emissions (*M* = 2.34; *SD* = 1.09) to be relatively low when measured on a five-point Likert scale [309].

Secondly, in respect to social capital, it emerges that trust in the media is lowest while trust in financial institutions also falls below the mean (see Table 4-3). This result reflects a pronounced trust deficit in the media [106,115], signalling a growing perception that some areas of journalism are increasingly entrenched in perpetuating a cycle of distrust and misinformation [310]. Although financial institutions have a critical role to play in securing a low-carbon economy [124,311], respondents doubt their capabilities and commitments towards steering the hydrogen transition. Supporting this observation, globally retrieved survey data such as the Edelman Trust Barometer has highlighted a sustained lack of public trust in financial institutions [310].

Such perspectives relay the underperformance of financial institutions in the eyes of the public, whereas renewable energy producers, and to a lesser extent GDNOs and Ofgem, are regarded as more trustworthy entities for fulfilling the net-zero mandate, although the overall prognosis remains mostly neutral. The apparent status quo resonates with findings reported in 2020, wherein 36% of survey respondents (N = 2000) expressed a neutral attitude regarding whether regulators such as Ofgem could be trusted to deliver a safe transition to hydrogen [118].

Thirdly, there is significant variation regarding perceptions of the respective components of the twin-track approach (see Section 4.3.3). A stronger preference is reported for green hydrogen (*M* = 6.86; *SD* = 0.59) compared to blue hydrogen (*M* = 6.17; *SD* = 0.85), which mirrors findings in other country contexts [121,134]. Interestingly, survey respondents expressed more support for green hydrogen in the short-term compared to the long-term (i.e. after 2030), while the reverse held true in the case of blue hydrogen.

Openness to blue hydrogen as a long-term production pathway (see Table 4-3 and Fig. 4-3) may reflect moderate levels of acceptance for CCS. Notably, 31% of UK survey respondents (N = 4145) expressed support for CCS, while 89% believed the technology would help combat climate change and reduce carbon emissions [309]. Based on available data, it can be inferred that perceptions of CCS could imply a somewhat positive outlook towards blue hydrogen, if better comprehended within the broader discussion of the hydrogen economy [131] and twin-track approach [22].

Fourthly, risk perceptions related to safety suggest that hydrogen may be viewed marginally safer than natural gas for cooking and heating applications, as well as pipeline transportation and underground storage (*M* = 5.83; *SD* = 0.12). Furthermore, the inclusion of a fifth measurement item regarding the overall safety level of hydrogen production, storage, transportation, and domestic appliances reiterates this finding (*M* = 5.68; *SD* = 1.86). By contrast, prior research has flagged sensitivities to the risks associated with hydrogen fuel in the context of transport applications [54], with moderate safety concerns expressed among German [209], South Korean [312], and Japanese respondents [144].

Contrary to prior research [89,148], this study observes no discrepancy regarding safety perceptions for hydrogen boilers (*M* = 5.93; *SD* = 2.01) and hydrogen hobs (*M* = 5.92; *SD* = 2.04). Overall, the results align somewhat closely to studies conducted in the UK [102] and Australia [106], which suggest a mix of neutral and positive safety perceptions regarding the impact of blending hydrogen into the gas grid for domestic use. Regarding perceived disruptive impacts, the results concur with findings in the literature, which cite moderate levels of preoccupation associated with the prospect of being temporarily disconnected from the gas grid [41,93]. However, impacts related to

street-level disruption and visits from gas engineers appear to be more tolerable (see Fig. 4-2), which is also consistent with qualitative findings on this topic [41].

At the level of cost-benefit appraisal, the results align with recent data from the UK government's Public Attitudes Tracker (PAT) [100], which indicates concerns over energy price hikes and fuel poverty are stronger than worries regarding reliability of energy supply. This discrepancy most likely reflects the current economic climate and ongoing energy crisis, which have exacerbated fuel poverty pressures in the UK [175]. Moreover, results from the PAT show that consumers have significantly stronger expectations for environmental benefits (see Table N-7), which also proved the case in this study (see Table 4-3 and Fig. 4-3).

In respect to affective response, positive emotions approximate a moderately strong response (i.e. > 3.0), while negative emotions equate to a neutral response (i.e. ~2.5). To an extent, domestic hydrogen may induce a sense of hope and confidence among parts of the public, which outweighs alternative feelings of fear, worry, and pessimism [103]. Crucially, optimism (PE4) registered as the strongest positive emotion, while worry (NE2) proved the principal negative emotion. This result could correspond directly to a sense of optimism for a cleaner energy future, coupled to concerns over the financial costs and broader socio-economic impacts of the transition. At the same time, it may be the case that the fear factor historically associated with hydrogen [313,314] is diminishing over time [147].

Additionally, the descriptive results for the domestic hydrogen acceptance (ACPT), suggest strong convergence when considering consumer perceptions across macro-, meso-, and micro-levels [33], as demonstrated in Fig. 4-3. However, it is anticipated that these dimensions may fluctuate by different magnitudes and possibly in alternative directions following the development of local hydrogen activities. Ruptures in public opinion and diverging consumer attitudes have already been witnessed in a short timeframe vis-à-vis the emergence of social resistance [315], which culminated in the cancellation of two proposed village trials for hydrogen homes.[35]

[35] Trials for Whitby village in (Ellesmere Port, Cheshire) Redcar (North Yorkshire) were cancelled in July and December 2023, respectively [429–431].

Finally, in terms of willingness to adopt domestic hydrogen (WTA), this analysis supports the study of Lozano et al. [69], which reported consistent results for attitude (i.e. happiness) towards using hydrogen for cooking, space heating, and hot water heating among Australians. However, the results deviate from the findings of Gordon et al. [148], which suggested an amplifying effect for behavioural intention when considering a hydrogen home compared to either appliance in isolation.

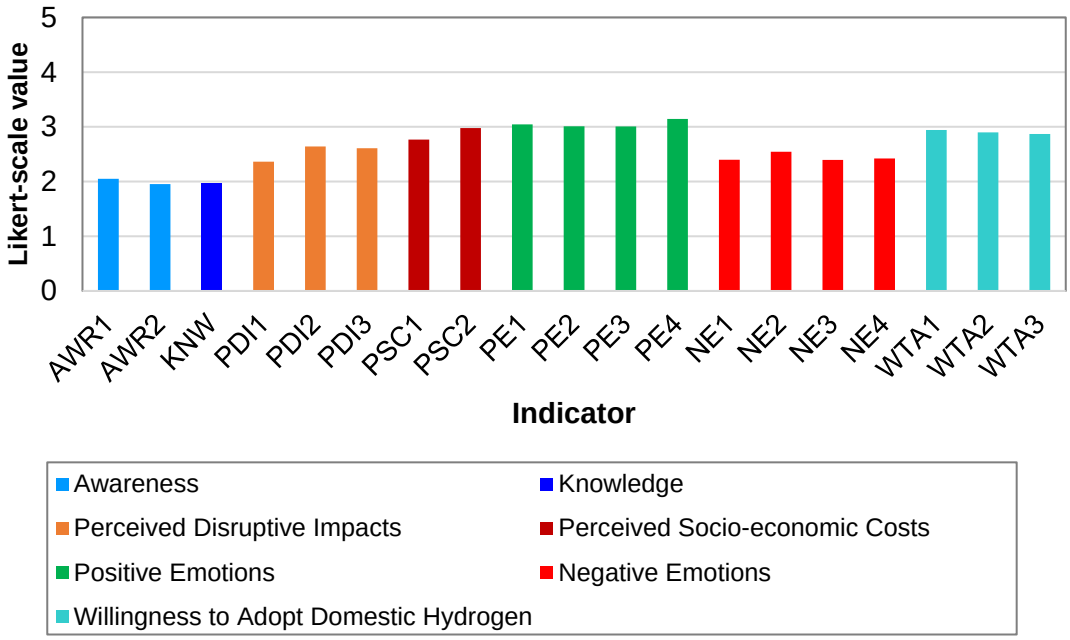


Fig. 4-2. Constructs measured on a five-point Likert scale.

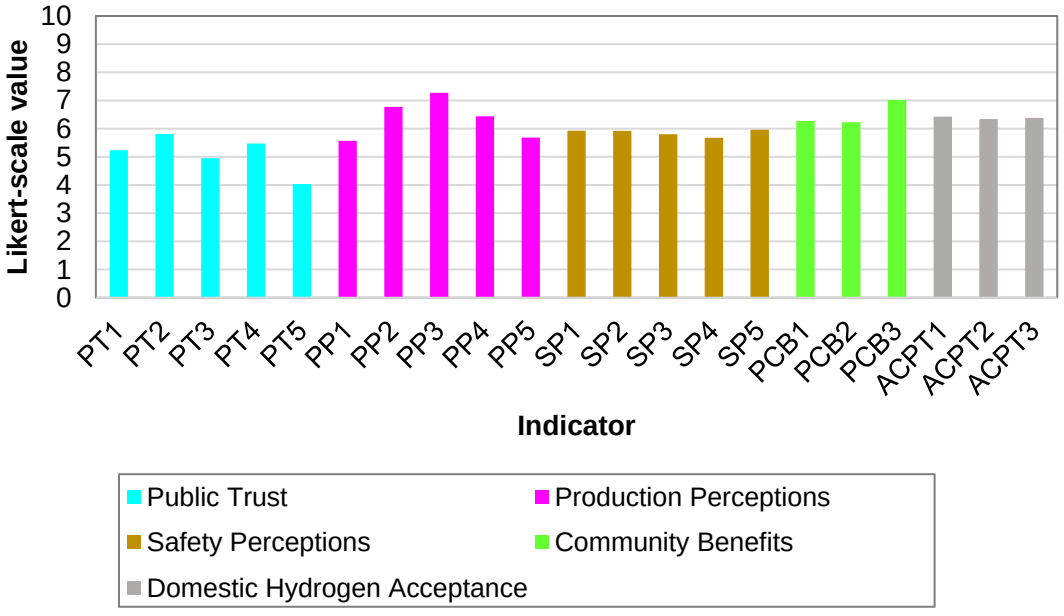


Fig. 4-3. Constructs measured on an eleven-point Likert scale.

Table 4-3. Summary of results from online survey questions on domestic hydrogen acceptance.

Acceptance dimension and construct(s)	Results at the construct level	Key findings and implications
Cognitive processes		
Awareness (AWR)	• AWR returned a mean score of 2.00 (*SD* = 0.99) as measured on a 5-point scale (1–5) • The descriptive results also indicated a pronounced lack of awareness regarding the UK Hydrogen Strategy (*M* = 1.69; *SD* = 1.00)[a] • Minimal difference between the two measures of AWR (*SD* = 0.07)	• Consistent with previous studies [69,99], awareness (and knowledge) is considerably low, confirming that the notion of 'hydrogen homes' is yet to penetrate the public consciousness
Knowledge (KNW)	• KNW returned a mean score of 1.96 (*SD* = 2.16) as measured on a 5-point Likert scale	• Subjective knowledge of hydrogen exhibits a considerably higher level of variance than hydrogen awareness, inferring that exposure to information is comparatively more similar than perceived levels of understanding
Social Capital		
Public Trust (PT)	• PT returned a mean score of 5.10 (*SD* = 2.41) as measured on an 11-point scale (0–10) • Moderate difference between the five measures of PT (*SD* = 0.68)	• Variability among public trust indicators suggests more public confidence in the actions of the renewable energy sector for supporting a cost-effective, efficient, and fair transition to hydrogen homes • Trust levels in Ofgem and GDNOs is relatively comparable, implying similar attitudes towards the energy regulator and companies managing the UK gas distribution network
Environmental attitude		
Production Perceptions (PP)	• PP returned a mean score of 6.35 (*SD* = 1.93) as measured on an 11-point scale • Moderate difference between the five measures of PP (*SD* = 0.72)	• To a degree, the survey results imply the potential undermining of the twin-track approach in terms of socio-political acceptance [33,131], as reflected in

	• The strongest preference is for an immediate focus on supporting green hydrogen production (PP3, i.e. before 2030) • Blue hydrogen production is more strongly supported as a long-term pathway (PP2) compared to a solution for the current decade (PP1)	the overall measure (PP5: *M* = 5.68) which fell below the average for this construct
Risk perceptions		
Safety Perceptions (SP)	• SP returned a mean score of 5.86 (*SD* = 2.03) as measured on an 11-point scale • Small difference between the five measures of SP (*SD* = 0.12)	• Safety perceptions are highly consistent across the measured items, suggesting hydrogen is viewed to be marginally safer than natural gas for heating and cooking purposes (SP1 and SP2), pipeline transportation (SP3), and underground storage (SP4)
Perceived Disruptive Impacts (PDI)	• PDI returned a mean score of 2.54 (*SD* = 0.97) as measured on a 5-point Likert scale • Small difference between the three measures of PDI (*SD* = 0.15)	• Respondents are more concerned with the prospect of being temporarily disconnected from the gas grid (PDI2; *M* = 2.64, *SD* = 0.98), whereas concerns are slightly lower regarding disruption from engineers and technicians (PDI3), and least for noise, traffic, and potential inconvenience from changes to infrastructure (PDI1)
Cost-benefit appraisal		
Perceived Socio-economic Costs (PSC)	• PSC returned a mean score of 2.87 (*SD* = 1.09) as measured on a 5-point Likert scale • Small difference between the two measures of PSC (*SD* = 0.15)	• The perceived socio-economic costs related to fuel poverty impacts (PSC2) measured higher than energy security concerns (PSC1), however, these two items are especially interrelated and display a relatively small difference
Perceived Community Benefits (PCB)	• PCB returned a mean score of 6.51 (*SD* = 2.08) as measured on an 11-point scale • Moderate difference between the five measures of PCB (*SD* = 0.44)	• Foremost, perceptions of environmental benefits (PCB3) are markedly higher than perceived economic (PCB1) and social benefits (PCB2), which explains the observed variance and suggests an underlying acknowledgement of the need for low-carbon energy technologies

Affective response		
Positive Emotions (PE)	• PE returned a mean score of 3.05 (*SD* = 0.99) as measured on a 5-point Likert scale • Minimal difference between the four measures of PE (*SD* = 0.06)	• 'Optimism' (PE4) registered as the strongest positive emotion (*M* = 3.15, *SD* = 1.00), whereas 'satisfaction' levels (PE1) were marginally lower, followed by 'calm' (PE2) and 'confidence' (PE3) which were equivalent, suggesting that feelings of hope for a domestic hydrogen future may outweigh other positive emotions
Negative Emotions (NE)	• NE returned a mean score of 2.44 (*SD* = 1.08) as measured on a 5-point Likert scale • Minimal difference between the four measures of NE (*SD* = 0.07)	• 'Worry' (NE2) registered as the strongest negative emotion (*M* = 2.55, *SD* = 1.06), followed by 'pessimism' (NE4), 'discontent' (NE1) and 'fear' (NE3), which had comparable mean scores, inferring that concern over hydrogen homes may outweigh other negative emotions
Social acceptance		
Domestic hydrogen acceptance (ACPT)	• ACPT returned a mean score of 6.39 (*SD* = 2.21) as measured on a 11-point scale • Minimal difference between the three measures ACPT (*SD* = 0.04)	• Socio-political (ACPT1: *M* = 6.43, *SD* = 2.10); community (ACPT2: *M* = 6.34, *SD* = 2.23); and individual acceptance (ACPT3: *M* = 6.38, *SD* = 2.28) are comparable, indicating a relative equilibrium when accounting for the macro-, meso-, and micro-scales [33]
Adoption intention		
Willingness to adopt domestic hydrogen before 2030 (WTA)	• WTA returned a mean score of 2.90 as measured on a 5-point Likert scale • Negligible difference between the three measures of WTA (*SD* = 0.04)	• Willingness to adopt a hydrogen boiler (WTA1: *M* = 2.94, *SD* = 1.00); hydrogen hob (WTA2: *M* = 2.90, *SD* = 1.01); and hydrogen home (WTA3: *M* = 2.87, *SD* = 1.04) proved highly comparable, mirroring the results for domestic hydrogen acceptance

[a] Although this item was dropped from the Awareness (AWR) construct as reliability and validity could not be established, the data provides valuable insights.

4.6.2 Measurement model assessment

This study operationalises ten exogenous constructs and two endogenous constructs, which are measured reflectively. Whereas a formative construct is caused by its indicators – with arrows points towards the construct – in a reflective model the latent construct exists (in an absolute sense) independent of its indicators [316]. Thus, variation in the construct causes variation in the measurement items, but the items do not cause variation in the construct [316,317]. Therefore, in a reflective model, arrows point from the construct to the indicators, since items are highly correlated and interchangeable [318], as is the case in this study.

For example, indicators such as economic, social, and environmental benefits are assumed to be influenced by an underlying latent construct [319,320], namely, perceived community benefits. More technically, the set of indicators represents a "measurement error-prone manifestation" of the underlying latent construct [248]. When measuring reflective constructs, four criteria should be met: item reliability, internal consistency reliability, convergent validity, and discriminant validity [320]. Critically, an instrument cannot be considered valid unless reliability is established [322].

4.6.2.1 Item reliability and internal consistency reliability

Item reliability is concerned with whether a measurement instrument performs consistently (i.e. scale reliability), which can be assessed using Cronbach's Alpha (CA). Reliability is best supported when an indicator loading measures above 0.708 [323], which implies that the construct accounts for more than 50 per cent of the indicator's variance [48]. Two indicators fell marginally below the preferred threshold value, namely, ST1 (0.698) and PDI1 (0.687), which is unproblematic for exploratory social science research involving new measurement items [318,324]. Although PP1 (0.550) had a relatively low CA, this indicator also warranted retention since related reliability and validity requirements were fulfilled [318,324]. Importantly, it is more conceptually sound to retain an indicator for content validity than to remove it purely on grounds of a low CA value [324].

Composite Reliability (CR) provides a better measure of internal consistency than CA, since items are weighted according to the individual indictor loadings per construct [48]. Homogeneity is supported when CR values exceed 0.70 [318], while ≥0.60 is

acceptable for exploratory research [325] such as this study. As reported in Table 4-4 (see Table N-6), both measures of CR exceeded 0.70 [48,326] (i.e. Dillon-Goldstein rho_c (ρ_C) and Henseler and Dijkstra rho_a (ρ_A)).

4.6.2.2 Convergent validity and discriminant validity

Convergent validity is concerned with whether each construct converges to explain the variance of its indicators [48], which was met since the average variance extracted (AVE) exceeded 0.50 for all constructs [318,325], as reported in Table 4-4. Relatedly, discriminant validity assesses whether a construct can be considered empirically distinct within the model [48]. Thresholds for establishing discriminant validity were met, as reported in Table 4-5 and described in Appendix N (see Table N-8 and Table N-9). Finally, no instances of multicollinearity were observed, variance inflation factor (VIF) scores were below the more stringent threshold of 3.0 in all cases [323].

Table 4-4. Assessment of reliability, convergent validity, and multicollinearity.

Construct	CA[a]	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Awareness	0.797	0.836	0.906	0.829[b]	1.346
Public trust	0.864	0.890	0.900	0.644	1.504
Production Perceptions	0.816	0.845	0.870	0.578	1.599
Safety Perceptions	0.918	0.920	0.939	0.754	1.575
Perceived Disruptive Impacts	0.758	0.813	0.859	0.673	1.259
Perceived Socio-economic Costs	0.730	0.736	0.881	0.787[a]	1.427
Perceived Community Benefits	0.808	0.813	0.886	0.721	2.066
Positive Emotions	0.881	0.885	0.918	0.737	1.468
Negative Emotions	0.869	0.900	0.909	0.715	1.409
Domestic Hydrogen Acceptance	0.922	0.922	0.951	0.865	n/a
Willingness to Adopt Domestic Hydrogen	0.934	0.934	0.958	0.883	n/a

[a] Calculated according to the average covariance divided by the average total variance (i.e. the average correlation shared between indicators and a given latent construct [326]). Since items are unweighted, CA tends to underestimate internal consistency reliability [49].

[b] Since Awareness (AWR) and Perceived Socio-economic Costs (PSC) have two indicators, the AVE is by default larger than 0.50. The result is reported for consistency.

Table 4-5. Heterotrait-monotrait results for assessment of discriminant validity.

	AWR	ACPT	KNW	NE	PCB	PDI	PSC	PE	PP	PT	SP	WTA
AWR												
ACPT	0.190											
KNW	0.537	0.159										
NE	0.080	0.376	0.113									
PCB	0.111	0.779	0.086	0.256								
PDI	0.064	0.346	0.094	0.511	0.197							
PSC	0.073	0.438	0.161	0.530	0.437	0.392						
PE	0.294	0.610	0.297	0.115	0.527	0.153	0.249					
PP	0.247	0.673	0.244	0.237	0.638	0.193	0.329	0.404				
PT	0.235	0.588	0.250	0.118	0.520	0.144	0.122	0.428	0.473			
SP	0.088	0.518	0.135	0.125	0.640	0.036	0.159	0.403	0.413	0.488		
WTA	0.279	0.675	0.297	0.240	0.514	0.219	0.287	0.674	0.418	0.348	0.368	

AWR = Awareness; ACPT = Domestic Hydrogen Acceptance; KNW = Knowledge; NE = Negative Emotions; PCB = Perceived Community Benefits; PDI = Perceived Disruptive Impacts; PSC = Perceived Socio-economic Costs; PE = Positive Emotions; PP = Production Perceptions; PT = Public Trust; SP = Safety Perceptions; WTA = Willingness to Adopt Domestic Hydrogen.

4.6.3 Structural model assessment

4.6.3.1 Results at the construct level

The bootstrap method with 5000 sub-samples was applied to test the direction, strength, and significance of proposed hypotheses [304], as reported in Table 4-6. Firstly, cognitive processes – awareness (AWR) and knowledge (KNW) – had a non-significant effect on social acceptance, although awareness exerted a stronger influence between the two constructs. This result suggests a consistent dynamic between awareness and knowledge, whereby these interrelated constructs mirror one another as poor predictors of domestic hydrogen acceptance at this stage of the transition.

Public trust (PT) had a positive and significant influence on domestic hydrogen acceptance (β = 0.198, t = 10.207, ρ < 0.001), implying that the transition will be influenced by public perceptions related to the capabilities and credibility of different actors and stakeholders. Regarding the environmental dimension linked specifically to production perceptions (PP), a significant positive effect is observed (β = 0.214, t = 10.897, ρ < 0.001), which can be traced foremost to consumer preferences for a green hydrogen pathway, as described in Section 4.3.3.

In terms of perceived risks, safety perceptions (SP) of hydrogen and the perceived disruptive impacts (PDI) of the switchover process are seen to largely neutralise one another. Nevertheless, the negative effect stemming from perceived disruptive impacts (β = -0.092, t = 5.450, ρ < 0.001) exceeds the positive association between safety perceptions and social acceptance (β = 0.058, t = 2,883, ρ = 0.004), which suggests risk perceptions are somewhat prominent.

At the level of cost-benefit appraisal, perceived community benefits is the strongest predictor of domestic hydrogen acceptance (β = 0.276, t = 12.118, ρ < 0.001), whereas perceived socio-economic costs is a comparatively weak predictor (β = 0.058, t = 3,432, ρ = 0.001) but still significant as the 1% level. Lastly, both affective constructs (PE and NE) shape consumer attitudes towards hydrogen, with positive emotions exerting more influence than its negative counterpart (β = 0.217, t = 12.599, ρ < 0.001; β = 0.138, t = 8.325, ρ < 0.001).

Among the ten exogenous constructs incorporated in this study, eight proved significant predictors of domestic hydrogen acceptance at the 1% level (ρ < 0.01), with

awareness and knowledge proving non-significant at this early stage of the technology life cycle (see Fig. 4-4) [327]. Accordingly, constructs belonging to the cognitive dimension returned insignificant effects, whereas other dimensions proved significant at the 1% level. Finally, the relationship between domestic hydrogen acceptance and willingness to adopt domestic hydrogen proved significant (β = 0.628, t = 41.587, ρ < 0.001), thereby validating the tenets of established behavioural theories [55,225].

Table 4-6. Results of path analysis and hypothesis testing.

Hypothesis	β coefficient (SD)	t-statistic	ρ-value	f^2	Result
H1: AWR → (+) ACPT	0.019 (0.015)	1.236	0.217	0.001	Rejected
H2: KNW → (+) ACPT	-0.008 (0.016)	0.513	0.608	0.000	Rejected
H3: PT → (+) ACPT	0.198 (0.020)	10.207	<0.001	0.079*****	Accepted
H4: PP → (+/-) ACPT	0.214 (0.020)	10.897	<0.001	0.085*****	Accepted
H5: SP → (+/-) ACPT	0.058 (0.020)	2.883	0.004	0.006	Accepted
H6: PDI → (-) ACPT	-0.092 (0.017)	5.450	<0.001	0.020	Accepted
H7: PSC → (-) ACPT	-0.058 (0.017)	3.432	0.001	0.007	Accepted
H8: PCB → (+) ACPT	0.276 (0.023)	12.118	<0.001	0.111*****	Accepted
H9: PE → (+) ACPT	0.217 (0.017)	12.599	<0.001	0.097*****	Accepted
H10: NE → (-) ACPT	-0.138 (0.017)	8.325	<0.001	0.041*****	Accepted
H11: ACPT → (+) WTA	0.628 (0.015)	41.587	<0.001	0.650***	Accepted

******* Large effect size (≥ 0.35)
***** Small effect size (i.e. 0.02–0.15)
No effective size = < 0.02
Medium-sized effect = 0.15–0.35

4.6.3.2 Results across acceptance dimensions

In summary, the following constructs have a small effect on social acceptance (i.e. f^2 > 0.02): public trust; production preferences; perceived community benefits; positive emotions; and negative emotions. However, safety perceptions, perceived disruptive impacts, and perceived socio-economic costs fall below the cut-off value suggested by Cohen [328]. Foremost, the dimensions of environmental attitude (i.e. production perceptions), affective response (i.e. positive and negative emotions), and social capital (i.e. public trust) predict social acceptance to a similar extent, followed by cost-benefit appraisal (i.e. perceived socio-economic costs and perceived community benefits), and risk perceptions (i.e. safety perceptions and perceived disruptive impacts), as reported in Table 4-7.

Table 4-7. Assessment of dimensions predicting domestic hydrogen acceptance.

Construct dimension	*β* coefficient	*t*-statistic	*ρ*-value	f^2	Result
Cognitive processes[a]	0.014	0.875	0.413	0.001	Rejected
Social capital[b]	0.198	10.207	<0.001	0.079*	Accepted
Environmental attitude[c]	0.214	10.897	<0.001	0.086*	Accepted
Risk perceptions[d]	0.075	4.167	0.002	0.013	Accepted
Cost-benefit appraisal[e]	0.167	7.775	0.001	0.059*	Accepted
Affective response[f]	0.178	10.462	<0.001	0.069*	Accepted

***** Small effect (i.e. > 0.02)
[a] Calculated as the mean value of *β* coefficients for AWR and KNW.
[b] Reflected by the *β* coefficient of ST.
[c] Reflected by the *β* coefficient of PP.
[d] Calculated as the mean value of *β* coefficients for SP and PDI.
[e] Calculated as the mean value of *β* coefficients for PSC and PCB.
[f] Calculated as the mean value of *β* coefficients for PE and NE.

4.6.3.3 Results from mediation analysis

The model shows strong support for the mediating role of domestic hydrogen acceptance. In all but two cases, complementary partial mediation was observed, with results adhering to the order reported for direct effects between antecedent constructs and domestic hydrogen acceptance (see Table 4-8). Foremost, domestic hydrogen acceptance positively mediates the relationship between perceived community benefits and willingness to adopt domestic hydrogen (β = 0.173, t = 11.689, ρ < 0.001), while the strongest negative mediation effect occurs in relation to negative emotions (β = -0.087, t = 8.134, ρ < 0.001). However, at the cognitive dimension, both hypotheses are rejected in view of non-significant results (AWR: ρ = 0.218; KNW: ρ = 0.621).

Table 4-8. Results of path analysis and hypothesis testing for mediation effects.

Hypothesis	*β* coefficient (SD)	*t*-statistic	*ρ*-value	Result
H12a: AWR → ACPT (+) → WTA	0.012 (0.010)	1.231	0.218	Rejected
H12b: KNW → ACPT (+) → WTA	-0.005 (0.010)	0.495	0.621	Rejected
H12c: PT → ACPT (+) → WTA	0.124 (0.012)	10.125	<0.001	Accepted
H12d: PP → ACPT (+/-) → WTA	0.133 (0.012)	10.773	<0.001	Accepted
H12e: SP → ACPT (+/-) → WTA	0.037 (0.013)	2.882	0.004	Accepted
H12f: PDI → ACPT (+) → WTA	-0.058 (0.011)	5.367	<0.001	Accepted
H12g: PSC → ACPT (+) → WTA	-0.036 (0.011)	3.373	0.001	Accepted
H12h: PCB → ACPT (+) → WTA	0.173 (0.015)	11.689	<0.001	Accepted
H12a: PE → ACPT (+) → WTA	0.137 (0.012)	11.519	<0.001	Accepted
H12g: NE → ACPT (+) → WTA	-0.087 (0.011)	8.134	<0.001	Accepted

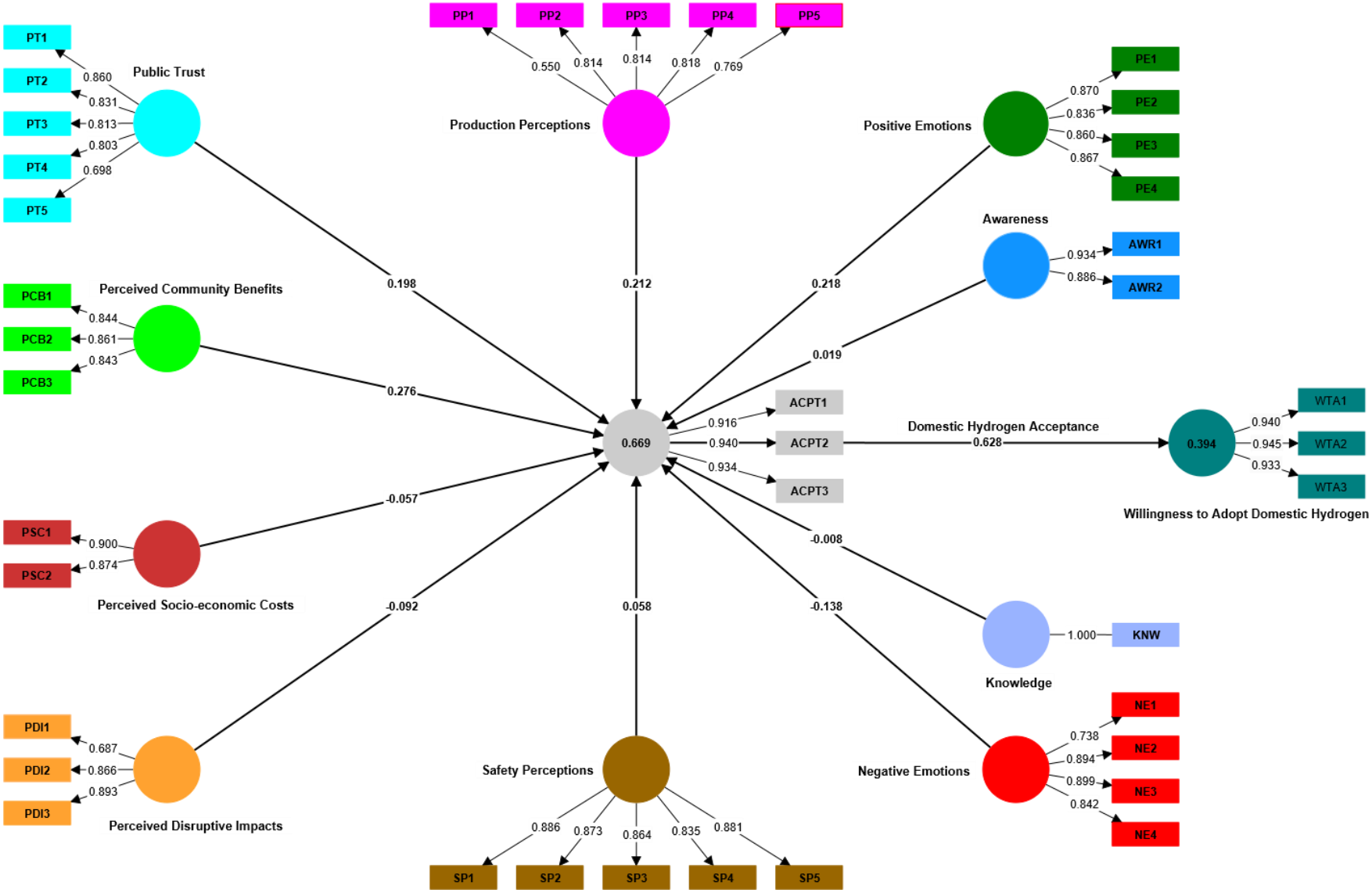


Fig. 4-4. Structural model path coefficients for the DHAM.

4.6.4 Importance-performance map analysis

As a decision-making tool [329,330], importance-performance map analysis (IMPA) [331] provides a means for deriving additional insights at both the construct and indicator level, thereby enabling triangulation with descriptive findings (see Section 4.6.1) and PLS-SEM results (see Section 4.6.3).

The IMPA plots unstandardised total effects (i.e. importance on the x–axis) against the average value of latent variable and their indicators on a scale of 0–100 (i.e. performance on the y–axis) to identify areas of strategic relevance [258]. Foremost, constructs located at the bottom far quadrant of the IMPA – corresponding to high importance but low performance for domestic hydrogen acceptance – signify opportunities for leveraging interventions [258]. Foremost, IMPA aids in identifying constructs of strategic value [331–333], which may be targeted through subsequent policy making efforts, communication campaigns, and managerial action [334,335].

Increasingly, sustainability scholars have adopted IMPA [336], as a tool to support optimal resource allocation strategy [335] and strategic decision-making in a range of contexts (see Appendix N). Moreover, internalising results from an IMPA is especially critical during times of economic instability [337] such as the current energy crisis [175,338]. To carry out an IMPA on domestic hydrogen acceptance (ACPT), the guidelines provided by Ringle and Sarstedt [331] are applied to understand the influence of endogenous constructs (see Section 4.6.4.1) and specific indicators (see Section 4.6.4.2).

4.6.4.1 IMPA for endogenous constructs

Firstly, an IMPA is carried out for the direct predecessors of domestic hydrogen acceptance, as visualised in Fig. 4-5 (see Table N-10 and Fig. N-5). Among the ten exogenous constructs analysed, negative emotions and perceived disruptive impacts rank in the middle in terms of importance: PCB, PE, PP, ST, **NE**, **PDI**, SP/PSC, AWR, KNW. There is clear overlap and interacting effects between the positive side of the hydrogen acceptance matrix [103] focused on perceived community benefits, production preferences, and public trust. These areas transmit to higher levels of optimism, confidence, and satisfaction with the promise of socio-economic and environmental benefits through the deployment of hydrogen homes.

Interestingly, safety perceptions and perceived socio-economic costs have equal total effects, but are separated on the IMPA due to their respective positive and negative influence on social acceptance. The two constructs are further distinguished in terms of their performance metrics, with safety perceptions outperforming perceived socio-economic costs by 12 units. As a result, there is more strategic value in targeting improvements in perceived socio-economic costs when choosing between these two constructs in isolation (see Fig. N-6). However, as illustrated by the rank order, neither construct falls within the priority cluster for bolstering social acceptance more directly. The IMPA further corroborates the weak impact of awareness and knowledge at this stage of the transition, while underscoring the importance of perceived community benefits.

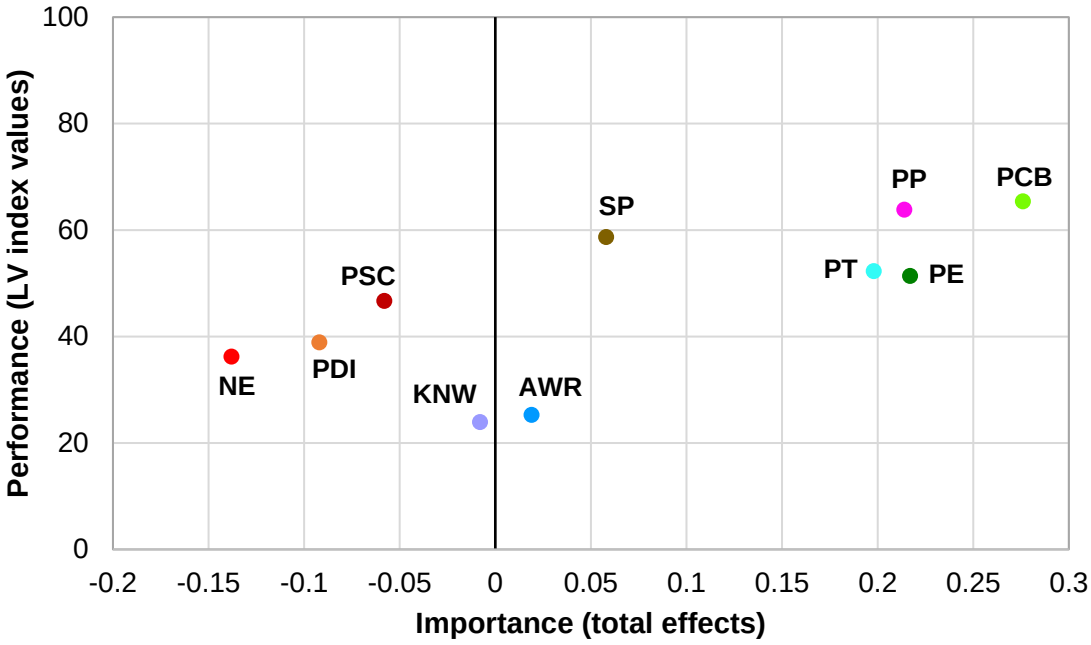


Fig. 4-5. Importance-performance map analysis for endogenous constructs.

Blue = Awareness (AWR); Lilac = Knowledge (KNW); Turquoise = Public Trust (PT); Lavender = Production Preferences (PP); Brown = Safety Perceptions (SP); Orange = Perceived Disruptive Impacts (PDI); Dark red = Perceived Socio-economic Costs (PSC); Bright green = Perceived Community Benefits (PCB); Dark green = Positive Emotions (PE); Red = Negative Emotions (NE).

4.6.4.2 IMPA for construct indicators

To complete the assessment, the IMPA analysis is extended to the indicator level (see Table N-11). Fig. 4-6 displays indicators with an effect size of 0.05 and higher, with the x-axis is reduced to 0.04 to increase readability. Four constructs are accounted for

in the IMPA at the indicator level: perceived community benefits (all indicators); positive emotions (all indicators); production perceptions (excluding PP1); and public trust (excluding PT3 and PT5).

The following conclusions support observations from the descriptive statistics reported in Section 4.6.1. Firstly, indicators related to perceived community benefits represent the foremost target area for elevating social acceptance, with environmental benefits (PCB3) carrying the most potential impact and outperforming economic (PCB1) and social benefits (PCB2), as well as all other indicators.

Interestingly, this result contradicts one study conducted in the North of England (N = 578), wherein survey respondents perceived significantly higher socio-economic benefits from hydrogen, as opposed to environmental benefits [119]. However, the study in question [119] had an inherently industrial and place-specific framing around efforts to establish a 'UK hydrogen corridor' between Leeds and Teesside, which likely explains why respondents envisioned substantial socio-economic benefits around job creation and industrial reinvigoration. Strikingly, based on experimental evidence from the virtual reality lab (i.e. using a between-subject design implementing two different treatments), Hoffman et al. [339] observed a critical finding: German respondents express higher support for green hydrogen when the focus is solely on the benefits of climate protection, as opposed to energy security and climate protection.

The IMPA aligns to results from the PAT [100], which showed that self-rated happiness (i.e. consumer acceptance) in relation to local energy infrastructure (i.e. onshore wind farms and solar panel farms) stems primarily from the perception of environmental benefits, whereas socio-economic benefits are of secondary importance [100] (see Table N-7). Furthermore, support for more traditional renewables such as onshore wind and solar farms is strongly linked to perceptions regarding emissions reduction [309], underlining the importance of perceived environmental impacts.

Secondly, there is little to distinguish between the four positive emotions measured in this survey, although optimism presents additional importance for garnering social acceptance. Notably, positive emotions stem from reactions towards other factors such as costs, benefits, and risks, which may explain why this construct has a mid-level performance. Accordingly, the IMPA suggests more resources should be allocated towards promoting a green hydrogen production pathway (PP3 and PP4) in

line with the promise of environmental benefits, which may reinforce positive perceptions and emotions. To this end, evidence suggests that renewable energy producers (PT2) are the most trusted entity for supporting the hydrogen transition.

It follows that renewable energy producers have a primary role in supporting the social acceptability of the hydrogen homes, while GDNOs (PT1) and Ofgem (PT4) have a complementary responsibility, which is somewhat more secondary in the eyes of the public at the present time. However, it should be stressed that the collapse of the Whitby village trial may have cast significant public doubt over the capabilities and intentions of GDNOs [340,341], which would need to be rapidly reversed if domestic hydrogen is to be given a green light by the government after 2026 [22].

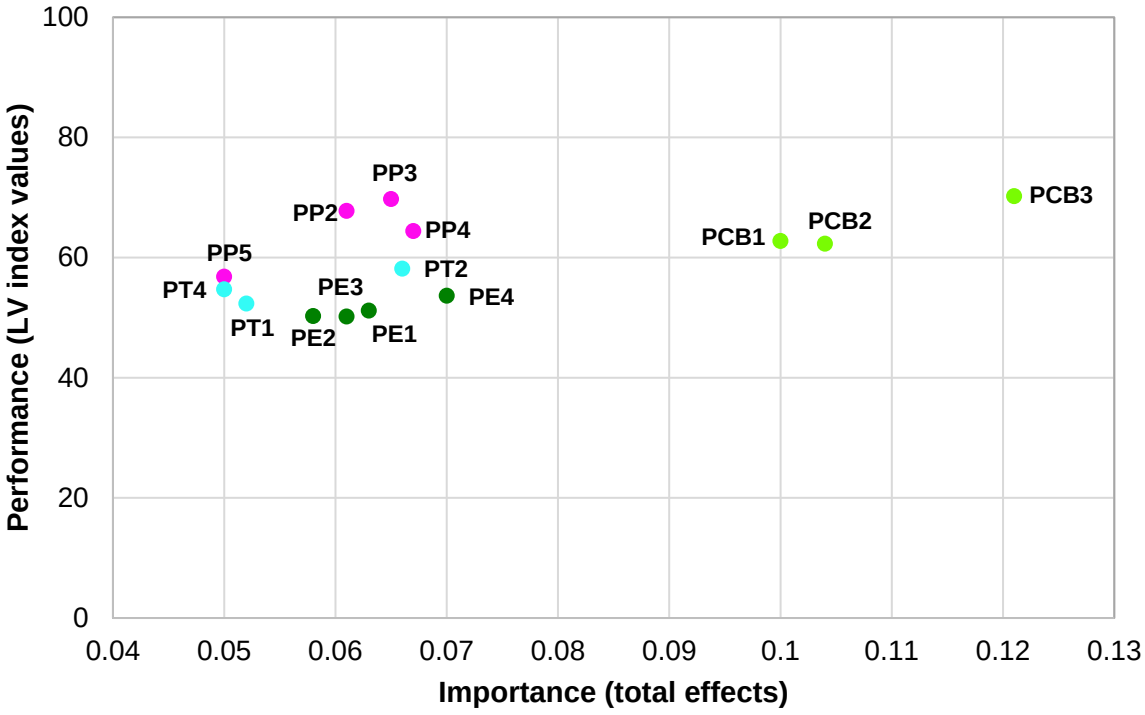


Fig. 4-6. Importance performance map analysis for top 14 indicators.

Turquoise = Public trust (PT); Lavender = Production Preferences (PP); Bright green = Perceived Community Benefits (PCB); Dark green = Positive Emotions (PE).

4.6.5 Assessment of predictive power

Traditionally, PLS-SEM practitioners have relied on assessing the path model's in-sample explanatory power [284,342], which is typically assessed using the coefficient of determination (R^2) [79]. R^2 reports the proportion of variance in the endogenous construct (i.e. domestic hydrogen acceptance) that can be explained by other constructs in the model. However, R^2 offers no specific guidance as to the out-of-

sample predictive power of the model, which requires “estimating the model on a training (analysis) sample and evaluating its predictive performance on data other than the training sample” [270:2324].

Thus, as a causal-predictive modelling approach [343], it is important to evaluate results from PLS-SEM in terms of both explanatory and predictive power [288,342,344]. Foremost, adherence to assessing out-of-sample predictive power is critical for theory development and validation, in addition to determining whether the modelling results can reliably inform policy making and strategic planning for a prospective transition to hydrogen homes.

4.6.5.1 In-sample predictive power

As a rule of thumb, Henseler et al. [272] suggest that R^2 values of 0.25, 050, and 0.75 correspond to weak, moderate, and strong effect sizes. However, lower R^2 values are anticipated and acceptable when examining emerging phenomena, such as low-carbon energy acceptance [224] or social media-related behaviour [321]. Therefore, R^2 should be considered as relative measure, whereby lower values typically reflect the exploratory nature of emerging social science research [345]. In this study, R^2 measured 0.669 for domestic hydrogen acceptance, suggesting a moderate to strong level of in-sample predictive accuracy. However, the model’s explanatory power was more conservative in relation to willingness to adopt domestic hydrogen ($R^2 = 0.394$).

4.6.5.2 Out-of-sample predictive power

Predictive benchmarking provides researchers with insights as to whether the proposed model outperforms a naïve baseline [276,346]. Initially, the quality of the structural model and its predictive relevance can be assessed through the blindfolding procedure [297], which returns the Stone-Geisser’s Q^2 value [347,348]. Following established guidelines, Q^2 values higher than 0, 0.25, and 0.50 suggest small, medium, and large predictive relevance of the PLS-path model [48].

The blindfolding procedure indicated strong predictive relevance for domestic hydrogen acceptance ($Q^2 = 0.663$) with each indicator supporting this result (ACPT1 = 0.583; ACPT2 = 0.583; ACPT3 = 0.556). However, the model demonstrated moderate predictive relevance in terms of adoption intention ($Q^2 = 0.346$), as supported by results at the indicator level (WTA1 = 0.299; WTA2 = 0.303; WTA3 = 0.314).

To further examine a model's out-of-sample predictive power [349], Shmueli et al. [270] developed the PLSpredict tool: "a holdout-sample-based procedure that generates case-level predictions on an item or a construct level to reap the benefits of predictive model assessment in PLS-SEM." More recently, Liengaard et al. [79] introduced the cross-validated predictive ability test (CVPAT) to better compare the predictive capabilities of different models, which has been extended by Sharma and colleagues [276]. The CVPAT performs "a pairwise comparison between theoretically derived competing models," and then "selecting the model with the highest predictive power based on a prespecified statistical significance level" [79].

Results suggest that the DHAM meets the minimum standard of predictive validity, since the model outperforms the indicator average (IA) prediction benchmark for both endogenous constructs (see Table 4-9), as reflected by a negative average loss difference. However, the model lacks strong predictive accuracy since it fails to outperform the more conservative linear model (LM) prediction benchmark [276]. Notably, the model demonstrates higher predictive capabilities when testing domestic hydrogen acceptance (t = 20.970) compared to willingness to adopt domestic hydrogen (t = 14.839), while the overall model yields the highest predictive power (t = 21.217).

Table 4-9. CVPAT benchmark and results for predictive ability test.

	PLS-SEM vs. Indicator average (IA)				
	PLS loss	**IA loss**	**Average loss difference**	***t*-value**	***p*-value**
Domestic Hydrogen Acceptance	2.079	4.874	-2.795	20.970	<0.001
Willingness to Adopt Domestic Hydrogen	0.721	1.039	-0.138	14.839	<0.001
Overall	1.400	2.956	-1.556	21.217	<0.001
	PLS-SEM vs. Linear Model (LM)				
	LM loss	**IA loss**	**Average loss difference**	***t*-value**	***p*-value**
Domestic Hydrogen Acceptance	2.079	2.063	0.016	1.046	0.296
Willingness to Adopt Domestic Hydrogen	0.721	0.626	0.096	7.903	<0.001
Overall	1.400	1.344	0.056	5.488	<0.001

4.6.6 Links between acceptance dimensions and constructs

4.6.6.1 Cognitive processes

This analysis suggests that cognitive processes linked to awareness and knowledge of hydrogen are currently non-significant factors of domestic hydrogen acceptance, which contradicts some of the evidence base presented in the literature (see Section 4.3.1). The results point towards a potential 'knowledge-attitude-action gap' [108,350] in respect to hydrogen homes, which implies awareness and knowledge may not translate directly into consumer support and raise adoption potential, ahead of decision-making (i.e. purchasing or rejection of the technology).

Notably, studies suggest that acquisition of technical knowledge does not necessarily translate into behavioural change in the context household energy consumption [350] or energy conservation in universities [351]. At the same time, it has been shown that awareness about river and drinking water does not significantly increase individual willingness to participate in sustainable water resource management [235]. Consequently, cognitive factors may fail to motivate citizens to support local hydrogen village trials, as reflected by anti-hydrogen campaigns in the North of England [352,353].

Although a recent meta-analysis of 24 quantitative studies showed that knowledge has a positive effect on consumer willingness to purchase HFCVs [354], Kar et al. [224] found that awareness has a non-significant effect on HFCV purchase intention (β = 0.035, t = 0.945). Moreover, recent evidence from the UK context suggests that knowledge and awareness may shape perceptions towards the twin-track approach but have limited influence on domestic hydrogen acceptance [131], which is partially confirmed by this study. Additionally, in the context of underground hydrogen storage in France, Barbier and Agnoletti [355] found that higher knowledge led to perceptions of greater environmental benefits among survey respondents and a more positive attitude (β = 0.524, ρ < 0.001). However, knowledge did not significantly predict behavioural intention towards accepting or rejecting hydrogen storage in salt caverns [355].

Critically, when confronted with a knowledge deficit or faced with highly complex or technical information, consumers may bypass deep cognitive evaluations in favour of emotional responses which can act as decision-making heuristic [356]. In accordance

with findings in the literature [32,39], it follows that domestic hydrogen remains at the periphery of public thinking [101,102], which may constrain the influence of awareness and knowledge on social acceptance during the formative phase of the transition.

It follows that awareness and subjective hydrogen knowledge may have marginal influence on social acceptance and adoption intention; at least when information is somewhat scarce and plans remain more dynamic or tentative [22,23]. However, it should be noted that the model has a limitation in testing the effects of cognitive processes, since measurements indicators for objective knowledge construct failed to establish construct validity (see Section 4.7.2). Furthermore, in view of findings in the literature, it emerges that the influence of awareness and knowledge could prove technology-specific and somewhat place-specific within the context of the hydrogen transition.

4.6.6.2 Social capital

The results suggest public trust is a positive and significant predictor of domestic hydrogen acceptance, thereby establishing the importance of social and cognitive processes, whereas cognitive aspects in isolation are less impactful. This finding supports a rich literature documenting the role of public trust in shaping the acceptance of emerging energy technologies [38,74,222]. It is apparent that developing public trust in hydrogen production pathways, energy markets, and management of pipeline infrastructure is critical to the transition. By the same token, trust dynamics concerning the investment landscape and publicising of domestic hydrogen will shape prospects for the transition. Foremost, public trust is a prerequisite to enabling consumer confidence in the environmental, economic, and social benefits of hydrogen homes [119,357]. Public trust in the domestic hydrogen transition will be strengthened if stakeholders enshrine maximum commitments towards ensuring environmental health and human safety.

4.6.6.3 Environmental attitude

This study explored perceptions of hydrogen production pathways vis-à-vis the government's twin track approach, thereby gauging potential (environmental) preferences for blue and green hydrogen production [131]. At one level, Table 4-3 and Fig. 4-3 support qualitative results highlighting an implicit misunderstanding about the rationale of the twin-track approach [131].

At present, the inferred equivalence or balancing of the twin-track approach appears to be largely unrecognised by the public. This misrecognition obscures the apparent commitment towards ensuring complementarity over competition in realising the hydrogen economy [31]. While blue hydrogen is likely a necessity for achieving industrial decarbonisation [7], and may underpin the foundations of developing a national hydrogen economy in the UK [22], a clear and direct public communication campaign on hydrogen production pathways is yet to be invested in. Addressing misconceptions in the public sphere, which entails an important role for energy representatives, politicians, and media outlets, is crucial to legitimising the UK Hydrogen Strategy [22].

Furthermore, it should be emphasised that respondents received both written and visual information regarding the twin-track approach. Following a description of blue hydrogen production, these details included an explanation that green hydrogen currently remains "a less mature technology than SMR" (i.e. blue hydrogen), while "hydrogen production via electrolysis is somewhat more challenging and expensive to deploy at large-scale across the UK." Subsequently, respondents were informed about policy ambitions following the release of the UK Hydrogen Strategy in October 2021 [22]: "In April 2022, the government released the British Energy Security Strategy**,** which doubled the 2030 hydrogen production target (from 5 gigawatts to 10 gigawatts) and made a commitment *to at least 50%* '***green***' *hydrogen production* (i.e. sourced from renewables)" (emphasis as appeared in the online survey).

In view of the above information, it is conceivable that respondents would absorb additional cues, following the target increase, that green hydrogen production is the preferential near-term and long-term pathway. In isolation, this may have contributed towards stronger support for green hydrogen before 2030 (M = 7.28) compared to after this decade (M = 6.44). However, it would be expected that responses should also account for technology maturity levels; supporting the logic that blue hydrogen is less desirable as a long-term production pathway (M = 6.78) compared to deployment this decade (M = 5.57).

Following the logic of the twin-track approach [22], the reported trends are counterintuitive since blue hydrogen is anticipated to play an enabling role for facilitating the long-term move towards hydrogen production sourced from renewables

[358]. Consequently, an inverse phenomenon is observed regarding public perceptions of the temporal dynamics of the twin-track approach. Above all, these contradictory response patterns appeared to diminish support for the twin-track approach (*M* = 5.68), as illustrated in Fig. 4-3. Nevertheless, production perceptions emerged as the most significant predictor of domestic hydrogen acceptance. Critically, the prognosis for social acceptance appears to lie with scaling up green hydrogen production, which aligns to most international findings [69,121,359].

It follows that information provision may have played a somewhat unanticipated role in shaping public perceptions, which cannot be readily quantified or otherwise estimated. Consequently, the role of information in shaping public attitudes towards hydrogen production pathways and associated environmental perceptions [72,121] presents a focal point of future research.

4.6.6.4 Risk perceptions

As reported via descriptive analysis, both safety and disruptive impacts are perceived to be somewhat moderate. The former construct (SP) has a positive influence on social acceptance, owing to a general perception that hydrogen may be slightly safer than natural gas, whereas the latter (PDI) exhibits a negative association. Given the reported awareness and knowledge deficit, it is conceivable that the risk characteristics of hydrogen remain poorly understood by most consumers.

The modelling results suggest that consumers consider hydrogen fuel to incur similar risks to natural gas [360,361], which is partially consistent with findings in the literature [93,102,106]. At the same time, it is apparent that safety perceptions may vary according to different HETs, while cross-cultural differences could explain discrepancies in the recent literature (see Section 4.3.4). Additionally, it has been shown that support for HETs is positively associated to public trust in the provision of adequate safety precautions [69,93], which may be the presumption among respondents in this survey.

On the softer side of hydrogen-related risks, it is logical that consumers would wish to minimise the extent of disruptive impacts during the switchover process. However, whereas a recent literature review suggested the disruptive impacts of the switchover may rank as a ‘major’ barrier to domestic hydrogen acceptance [32], this study identifies this construct to be a somewhat less critical barrier.

Overall, it can be asserted that taken together, safety perceptions and perceived disruptive impacts have a largely neutralising effect on risk perceptions. Nevertheless, the perceived risks of hydrogen may be prone to sudden changes when activities are taken from the hypothetical to the real [352,362,363] and moreover, in the event of inevitable safety incidents [364,365].

4.6.6.5 Cost-benefit appraisal

The wider energy acceptance and emerging hydrogen acceptance literatures suggest perceived benefits may be the foremost predictor of social acceptance and technology adoption [39,180,189], which was corroborated in this study. Beyond the UK context (see Section 4.3.3), the modelling results echo findings from Norway, wherein perceived environmental benefits proved an important predictor of hydrogen acceptance [121]. Notably, the Norwegian study flagged the need to consider other acceptance factors such as “perceived cost, safety and economic benefits” [106:10], which has been addressed in this study but likewise requires further comparative assessment.

Perceptions of socio-economic costs are set to fluctuate according to the macro-economic environment, which currently dictates greater levels of concern over fuel stress implications than national energy security issues (see Table 4-3 and

Fig. ***4-2***). However, these two areas are highly intertwined, with the former capturing the more personal dimension against the socio-political dimension of the energy crisis. Given the premise that industrial reinvigoration and levelling up [41,366] should be embedded in the hydrogen transition [22], failure to create an acceptable safety net for households in fuel poverty and socio-economically deprived regions could lead to widespread social resistance.

4.6.6.6 Affective response

In addition to perceived benefits, emotional responses may be among the most critical predictors of HET acceptance [39], which proved the case in this study. Emotional responses may exhibit a comparatively stronger influence in the domestic energy context [194,367], wherein the lived experience of heating and cooking impacts consumer expectations and preferences [89,102]. Foremost, this study finds that positive emotions have a stronger influence on social acceptance than negative emotions, although the latter construct is also significant at the 1% level.

Ambitions for accelerating industrial decarbonisation are a driver of large-scale (hydrogen) production [7], which strongly underlies the techno-economic feasibility of hydrogen homes [31]. In parallel, policy and market decisions around the role of heat pumps [253,368], smart hybrid heat pumps [369], and other low-carbon technologies such as district heat networks [370] will shape emotional responses to hydrogen home appliances.

Given the interdependencies between energy resources and different hydrogen production pathways [371,372], 'perception spillover' effects may influence the acceptance dynamics of the broader hydrogen economy [373]. Notably, Westlake et al. [373] highlight the extent to which perception spillover from one energy technology such as fracking may influence public attitudes towards emerging low-carbon solutions. Specifically, the moratorium on fracking appears to have undermined the social acceptance of deep 'enhanced' geothermal systems compared to green hydrogen [373], which could present a cautionary tale for CCS and blue hydrogen [374].

4.6.6.7 Social acceptance and adoption intention

As conceptualised within the unified theory proposed by Gordon et al. [44], willingness to adopt domestic hydrogen mediates the relationship between domestic hydrogen acceptance and actual adoption, which currently remains hypothetical and may be delayed for several years if ultimately realised [22,93]. Consequently, during the pre-deployment phase of the transition, it is more relevant to examine acceptance and adoption dynamics in relation to consumer attitudes and behavioural intentions.

To date, the literature on HFCVs strongly suggests that attitude has a positive influence on purchase intention [354], with Harichandan and Kar [298] reporting a large effect size in the Indian context (β = 0.538, t = 12.728, ρ < 0.001). Similarly, this study provides strong evidence that social acceptance positively predicts adoption intention for hydrogen home appliances (β = 0.628, ρ < 0.001, f^2 = 0.650). Interestingly, a recent meta-analysis on technology acceptance research undertaken by Marikyan and colleagues [375] showed that TAM outperforms both TPB and DoI in predicting attitude (β = 0.325) and behavioural intention (β = 0.328), as well as actual behaviour (β = 0.349). Encouragingly, the DHAM – through its multi-dimensional grounding and leveraging of antecedents postulated in the unified theory of domestic hydrogen

acceptance [44] – demonstrates strong effect sizes in predicting both social acceptance (e.g. PCB: β = 0.276) and adoption intention (β = 0.628).

Broadly, the finding aligns to the premise of the TPB and subsequent frameworks such as the TAM, while the R^2 results also support evidence presented in the literature. For example, meta-analyses indicate that the Theory of Reasoned Action (TRA) and its successor, the TPB, can explain on average between 40% and 50% of the variance in behavioural intention, and 19% to 38% of the variance in behaviour [376]. Subsequently, Armitage and Conner [434] found that variables within the TPB accounted for 39% and 27% of the variance in behavioural intention and behaviour, respectively. In a similar vein, the DHAM is less effective in explaining the variance in adoption intention (R^2 = 0.394) compared to social acceptance (R^2 = 0.669), which motivates the need for further exploration as reflected in the development of UTAUT [57,377]. In quantitative terms, the effect of each exogenous construct is reduced by around 37% due to mediating role of domestic hydrogen acceptance (e.g. PCB → DHA → WTA), compared to direct effects (see Table 4-10 and Table N-12), which is in line with prior observations.

4.6.6.7.1 Predicting changes through the innovation-decision process

To extend the core analysis focused on the DHAM, Fig. 4-7 operationalises willingness to adopt domestic hydrogen (WTA) as the sole endogenous construct in the model, thereby testing the direct effects of ten exogenous constructs on adoption intention. This adjustment reflects the explorative nature of PLS-SEM whereby different constructs and path relationships can be conceived and readily tested in software applications such as SmartPLS [304].

Following evaluation of the measurement model to establish construct reliability and validity (see Table N-13–Table N-16), the structural model was assessed for illustrative purposes to directly compare acceptance and adoption dynamics for hydrogen homes (see Table N-17). The rationale was to leverage the DHAM within the same analysis as a bridge to follow-up studies focused exclusively on adoption potential; recognising that other factors such as perceived technology attributes and financial perceptions will shape adoption dynamics, while mediating relationships may also be conceptualised [44]. As a result, Fig. 4-7 and Table 4-10 provide a starting point for anticipating the innovation-decision process [88] for hydrogen home

appliances, as extrapolated from online survey responses given during the pre-deployment stage of the technology transition. Notably, compared to the DHAM, the model displayed in Fig. 4-7 demonstrates higher in-sample predictive power (R^2 = 0.466), and moreover, greater out-of-sample predictive power (Q^2 = 0.459), as reported in Appendix N (see Table N-18 and Table N-19).

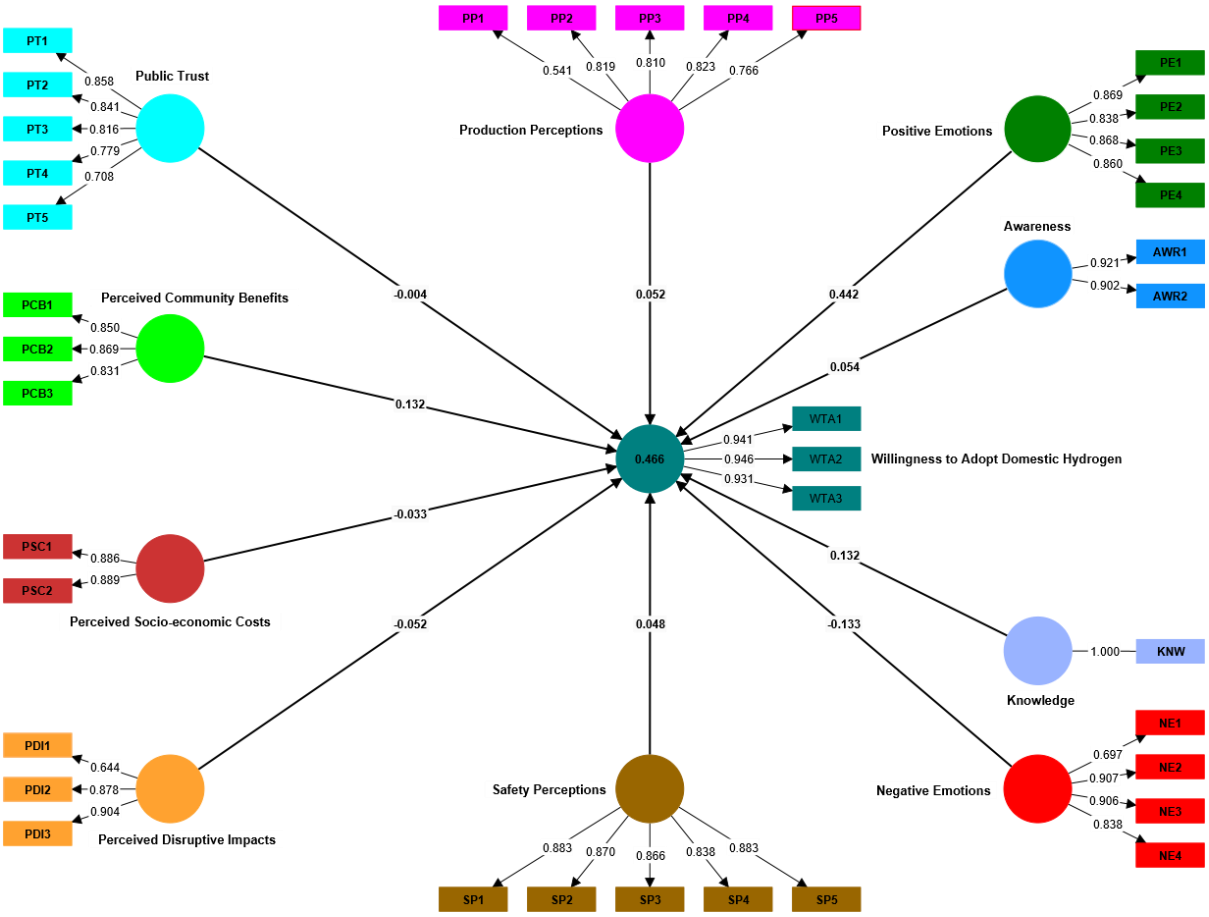


Fig. 4-7. Structural path coefficients for adoption intention.

The results show that the relative importance of different constructs will likely change during the initial stages of the innovation-decision process (i.e. from knowledge to persuasion to decision), wherein consumers also progress to different states of awareness and knowledge [88]. In turn, the influence of cognitive processes in shaping attitudes and perceptions toward hydrogen homes may increase (see Section 4.6.6.1). Table 4-10 shows support for this hypothesis since both awareness (ρ = 0.006) and knowledge (ρ < 0.001) are statistically significant predictors of willingness to adopt domestic hydrogen. Notably, subjective hydrogen knowledge has a stronger effect than low-carbon energy awareness, which suggests knowing the specific context may prove more meaningful than general awareness.

Table 4-10. Comparison between models for predicting domestic hydrogen acceptance and adoption.

	Model 1		Model 2	Comparison
	Construct$_X$ → DHA	**Construct$_X$ → DHA → WTA**	**Construct$_X$ → WTA**	**Difference in direct effects of Construct$_X$ on WTA compared to DHA**
Construct	**Structural path coefficient (β)**			
AWR	0.019	0.012	0.054***	+0.035 (significant increase)
KNW	0.019	-0.005	0.132***	+0.113 (significant increase)
PT	0.198***	0.124***	-0.004	-0.202 (significant decrease)
PP	0.212***	0.133***	0.052*	-0.160 (significant decrease)
SP	0.058***	0.037***	0.048*	-0.010 (significant decrease)
PDI	-0.092***	-0.058***	-0.052**	0.040 (significant decrease)
PSC	-0.057***	-0.036***	-0.033	0.024 (significant decrease)
PCB	0.276***	0.173***	0.132***	-0.144 (non-significant)[a]
PE	0.218***	0.137***	0.442***	+0.224 (non-significant)[b]
NE	-0.138***	-0.087***	-0.133***	-0.005 (non-significant)[c]

******* Statistically significant at the 0.1% level.
****** Statistically significant at the 1% level.
* Statistically significant at the 5% level.
[a] Results are statistically significant at the 0.1% level, but PCB has less impact in Model 2.
[b] Results are statistically significant at the 0.1% level, but PE has more impact in Model 2.
[c] Results are statistically significant at the 0.1% level, with NE having equivalent effects in both Models.

Except for emotional constructs (PE and NE), the remaining structural coefficients are weakened when evaluating adoption intention directly, however, there is notable variation in differences across certain constructs. Foremost, public trust (ρ = 0.856) and perceived socio-economic costs (ρ = 0.123) are non-significant in predicting willingness to adopt domestic hydrogen appliances, while the influence of production perceptions (ρ = 0.016) and safety perceptions (ρ = 0.035) are statistically significant at the 5% level, as opposed to the 0.1% level.

Additionally, the effect of perceived disruptive impacts is less pronounced (ρ = 0.010), whereas the effect of negative emotions is near equivalent between Model 2 (ρ = -0.133) and the DHAM (ρ = -0.138). By contrast, positive emotions has a substantially larger influence on adoption intention (β = 0.442) compared to social acceptance (β = 0.218), which suggests emotional response may prove more critical than cognitive processes in shaping market acceptance for hydrogen homes [32,33]. Finally, while this analysis emphasises the importance of perceived economic, social, and environmental benefits to the domestic hydrogen transition, Fig. 4-7 implies that subjective knowledge of hydrogen (β = 0.132) may prove equally important as

perceived community benefits (β = 0.132) in determining adoption intention for hydrogen homes.

4.7 Conclusions

As remarked by Parkison et al. [130], highly technical data on costs and emissions is often leveraged and misrepresented by groups with vested interests to sway policy makers and influence public opinion, especially in respect to the polarising debate around fossil-based and renewable-based hydrogen production technologies. Accounting for these dynamics, this study presents key findings on domestic hydrogen acceptance, as transmitted by the public and made accessible to a wide range of stakeholders through data visualisation techniques.

This research bridges a critical knowledge gap in the energy acceptance literature by comprehensively examining public perceptions of domestic hydrogen. In parallel, this study motivates the wider dissemination of PLS-SEM in energy acceptance research to support a deeper understanding of the conditions for accelerating low-carbon energy adoption. The following sub-sections complete the analysis by outlining key theoretical and empirical contributions, future research avenues, and practical implications which can be leveraged by policy makers and key stakeholders to support a 'hot transformation' for the residential sector [378].

4.7.1 Theoretical and empirical contributions

This research contributes to theory by developing and empirically validating a novel model of domestic hydrogen acceptance, which is conceptualised in Fig. 4-1). While prior work has explored the foundations for conceptualising a definitive framework [33,39,69], this study is the first to formalise a multi-dimensional model, while validating its explanatory and predictive capabilities using PLS-SEM. The DHAM is composed of ten exogenous constructs which underpin six socio-psychological dimensions, wherein five proved significant at the 1% level (see in Table 4-7).

It can be concluded that these dimensions and their corresponding constructs are significant predictors, together explaining nearly 67% of domestic hydrogen acceptance. Consequently, the model validates the efficacy of eight constructs (PT, PP, SP, PDI, PC, PCB, PE, and NE), although two constructs at the cognitive dimension (AWR and KNW) proved insignificant. Accordingly, this study makes an important empirical contribution, which may stimulate subsequent engagement with

PLS-SEM by hydrogen acceptance scholars. Notably, the need for this trajectory has been recognised by Harichandan and colleagues [224,298,379] when validating hypotheses in the context of HFCV adoption in India.

The DHAM provides the research community with a baseline model for examining consumer attitudes towards hydrogen homes. Findings from this research can be benchmarked against statistical results from other country contexts such as Australia [69] to help bridge conceptual and empirical understanding on hydrogen acceptance. Critically, this analysis reinforces the call for more robust quantitative assessments [39] to advance understanding on developing national hydrogen economies. Developing models with stronger explanatory and predictive power is a critical mechanism for embedding societal factors in the technological pursuit of large-scale, sustainable energy solutions, which may include establishing a global hydrogen economy.

4.7.2 Scope for developing the DHAM and future research agenda

This study focused on modelling the mediating role of social acceptance in predicting willingness to adopt domestic hydrogen, with inclusion of ten exogenous constructs. However, prior research highlights the value of considering the mediating role of other constructs such as public trust [222], and perceived risks, costs, and benefits [74,223,224]. For example, Montjin-Dorgelo [208] modelled trust and emotions as mediators when examining acceptance for hydrogen buses in the Netherlands, while Yang et al. [208,222] proposed a mediating role for public trust in the context of CCS technologies in China. Furthermore, the unified theory of domestic hydrogen acceptance posits a causal link between cognitive processes and safety perceptions, which should be examined in subsequent studies, alongside other relationships [44].

In addition to testing for mediation and moderation effects (e.g. influence of socio-demographic factors), further conclusions can be drawn by expanding the multi-dimensionality of certain constructs through new measurement items. For example, Calik and Ates [380] proposed a scale consisting of three dimensions and ten questions to help measure public awareness of hydrogen. Furthermore, survey items corresponding specifically to perceived economic, social, and environmental benefits would facilitate opportunities for developing a reflective-formative construct to increase theoretical parsimony and reduce model complexity [381] (see Fig. N-7).

Researchers may also adapt and extend the DHAM by developing a higher-order construct for public trust. Given the importance of public trust to facilitating energy acceptance, further modelling work is needed to evaluate consumer perspectives towards the government, energy industry, and other key stakeholders, as potential enablers of a socially acceptable transition to hydrogen homes. To this end, researchers can leverage opportunities to integrate additional constructs into the DHAM to unpack the trust dynamics of the domestic hydrogen transition.

Higher-order constructs could also be a viable technique for modelling production perceptions (i.e. operationalising blue and green hydrogen as lower-order constructs). Notably, a recent UK study asked respondents about their level of agreement regarding government investment in hydrogen production funded by a levy on people's energy bills [382], which could be used as a construct indicator in future studies. It follows that distilling socio-economic and environmental perceptions of hydrogen production pathways presents a fruitful area for further research. In sum, the baseline version of the DHAM can motivate more nuanced studies which employ techniques such as mediation and moderation analysis to model hydrogen acceptance [383,384]. Such measures would contribute towards improving the predictive power of the model to outperform the stricter linear benchmark employed in the CVPAT (see Table 4-9).

Another viable approach is to examine potential differences between consumer segments via a multigroup analysis (MGA) [82,385]. The efficacy of MGA has been demonstrated across a range of technology acceptance studies [386–388], leading to recent uptake among energy scholars [351,389]. MGA can help expand the evidence base, while supporting longitudinal, cross-cultural hydrogen acceptance studies. Future studies can also crystallise insights on perceived disruptive impacts by validating whether current assessments suggesting a tolerance period of around three days are accurate [41], while further clarifying the scope of expectations among different consumer segments [148,256].

Although the critical findings on cost-benefit appraisal are strongly supported by government data (see Table N-7), cross-comparative analysis of large datasets should be carried out to further validate the findings. Importantly, the selected survey instruments encountered a notable constraint for achieving a more robust comparison between perceived costs and benefits. Specifically, an intended third measure (i.e.

negative environmental impacts) of the original construct, *perceived costs*, could not be validated. This discrepancy may partially explain why the cost-benefit appraisal dimension is somewhat less significant than other dimensions (i.e. social trust, cognitive processes, environmental attitude, and affective response), as reported in in Table 4-7.

In follow-up research, the selected statement, “Switching from natural gas to hydrogen will have an insignificant impact towards reaching 'net-zero' (i.e. a reduction of the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050),” can be simplified to “*Switching from natural gas to hydrogen will have negative environmental impacts*” to establish construct validity. Despite this limitation, the modelling results provide critical insights regarding the pivotal dimension of cost-benefit evaluations, as highlighted in Section 4.6.6.6.

Relatedly, it is apparent that question framing and information provision materials can play a significant role in shaping survey responses, as recently documented by research groups in Australia [109] and Germany [339]. Future studies can better determine how information on hydrogen production methods may influence response patterns. Additionally, it is important to establish whether hydrogen safety perceptions change significantly when evaluated differently or in isolation, instead of being measured vis-à-vis natural gas. Foreseeably, as part of the dimension of risk perceptions, attitudes towards hydrogen safety may yield a negative or otherwise non-significant effect on acceptance.

There is also scope for better capturing the affective dimension through a wider range of emotional responses. Notably, the seminal study of Beaudry et al. [390] provides a robust framework for evaluating affective appraisals in relation to emotions concerning achievement (e.g. satisfaction), challenge (e.g. hope), loss (e.g. anger), and deterrence (e.g. fear). If follows that additional survey instruments can better account for the wide spectrum of emotional responses to domestic hydrogen [103].

Furthermore, multiple evidence streams are needed to ascertain whether positive emotions towards domestic hydrogen prevail, and moreover, how the dynamics of emotional response, alongside other factors [120], may change over time according to different policy prescriptions [392], party preferences [392], and media representations [393,394]. To an extent, Fig. 4-7 validates the notion that the

antecedents shaping public perceptions of hydrogen homes [32] will change throughout the innovation-decision process, and may vary considerably for social acceptance and adoption intention (see Table 4-10). Additionally, important insights could be extracted by comparing social acceptance across different measures in relation to hydrogen, CCS, nuclear and wind energy (onshore and offshore), thereby elucidating statistical relationships between these interrelated technologies, which would advance the contribution of Roddis et al. [395].

4.7.3 Practical contributions and policy implications

Beyond the theoretical dimension, there are several practical implications of this research. The study provides policy makers and key stakeholders such as GDNOs and boiler manufacturers with strategic insights for improving consumer engagement, information campaigns, and management decisions. Fig. 4-6 clearly translates the implications of the model, communicating the underlying need to couple green hydrogen production to community benefits, as a mechanism for increasing optimism and confidence in hydrogen homes.

At the same time, stakeholders should not overlook the importance of managing the disruptive impacts of the transition ahead of time, while pre-empting the risks of negative socio-economic effects. Such measures would help simmer negative emotions towards hydrogen at a time when energy vulnerabilities are high [175,396], as geopolitical stakes continue to increase around resources [171,172,397] and ideologies [168,398].

As the stakes for deploying low-carbon technologies continue to rise, this analysis can help steer critical discussion around potential synergies between hydrogen production pathways and community benefits to support a socially acceptable energy transition. In response, UK policy makers and key stakeholders should seek to leverage prospects for better packaging the synergistic effects of scaling up different hydrogen production methods. This measure could help support a more positive environmental attitude towards hydrogen across society, which may involve reconsidering the ‘twin-track’ framing, in view of its propensity for raising confusion, doubts, and scepticism among the public. Recasting the twin track production approach and justifying the role of blue hydrogen to the public are important starting points for facilitating social acceptance. In doing so, the government can take strides towards building knowledge

and awareness of hydrogen across society and supporting public trust in the hydrogen economy.

Government policies should aim to ensure ‘price promises’ [399] on hydrogen boilers are delivered by manufacturers to counteract perceived socio-economic risks. Furthermore, the government should dedicate adequate resources towards alleviating fuel poverty pressures, as part of its residential decarbonisation strategy and wider net-zero agenda [41,175]. Such measures would help improve public expectations for economic and social benefits trickling down to the community level [119].

Emotional responses to hydrogen may underlie social acceptance, especially at the individual and community level [39], with implications for attitudes towards safety, production, risks, costs, and benefits [44,193]. Strengthening positive emotions will weaken the impact of potential negative feelings towards hydrogen, which can be addressed more directly by minimising concerns over perceived socio-economic costs and disruptive impacts, while ensuring safety perceptions are decoupled from fears and negative imagery.

4.7.4 Supporting a hot transformation via hydrogen homes?

History has shown that a large-scale conversion to a new gas supply is plausible, both in the UK [161] and internationally [401,402], however, this era calls for a ‘hot transformation’ [379] which is clean, equitable, and timely. Agents of the energy transition including policy makers, GDNOs, and boiler manufacturers may leverage insights from this study to devise more holistic and reflexive solutions to instilling social acceptance into the fabric of the hydrogen transition. As noted by Papachristos [364:57] governance approaches for mitigating climate change call for “an iterative process of problem definition, intervention and response” to bridge the gap between different actor groups in pursuit of productive dialogues and constructive actions [403].

A hybrid, collaborative approach is needed to realise the potential economic, social, and environmental benefits of the hydrogen economy [16,404]; bearing in mind that the techno-economic feasibility of hydrogen homes and other HETs [31] must be established to facilitate social acceptance. Foremost, the implementation of HETs will be driven by cost factors and scalability [19,130], wherein techno-economic constraints must be tackled to support national hydrogen economies [19]. This calls for a whole-systems approach geared towards leveraging the synergistic benefits of

hydrogen production pathways, thereby advocating for complementarity over competition in delivering the twin-track approach [31].

A more unified vision between stakeholders supporting respective green gas [405–407] and electrification pathways [408,409] is desirable. Ideally, rifts between incumbents and new entrants should be narrowed by the vision (or re-envisioning) of the twin-track approach, and moreover, the pressing need to accelerate ‘deep’ decarbonisation [410]. Stronger levels of collaboration and unity could bolster public trust in the transition, while promoting the underlying tenets of the twin-track approach, which is needed to consolidate community and socio-political acceptance.

Ahead of a critical decision on the future of residential decarbonisation in the UK towards the mid-2020s [22,370], energy scholars should respond in kind by accelerating the adoption of state-of-the-art predictive modelling approaches. In conjunction with PLS-SEM, emerging methods such as machine learning [411,412] and artificial neural networking [413,414] should be harnessed as complementary techniques to enhance critical insights on the dynamics between domestic hydrogen acceptance and adoption intention.

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5 HETEROGENEOUS PREFERENCES FOR LIVING IN A HYDROGEN HOME: A MULTIGROUP ANALYSIS OF UK HOUSEHOLDS

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Statement of contributions

Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Conceptual framework; Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Supervision. **Anwar Haq:** Writing – review & editing, **Seyed Ali Nabavi:** Supervision.

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Highlights

- UK consumers have heterogeneous preferences for adopting hydrogen homes
- Perceptions of hydrogen production is a source of consumer heterogeneity
- Financial perceptions are homogenous during the formative stage of the transition
- Engagement with technology and the environment strengthens adoption potential
- Socio-structural variables may moderate adoption potential for hydrogen homes

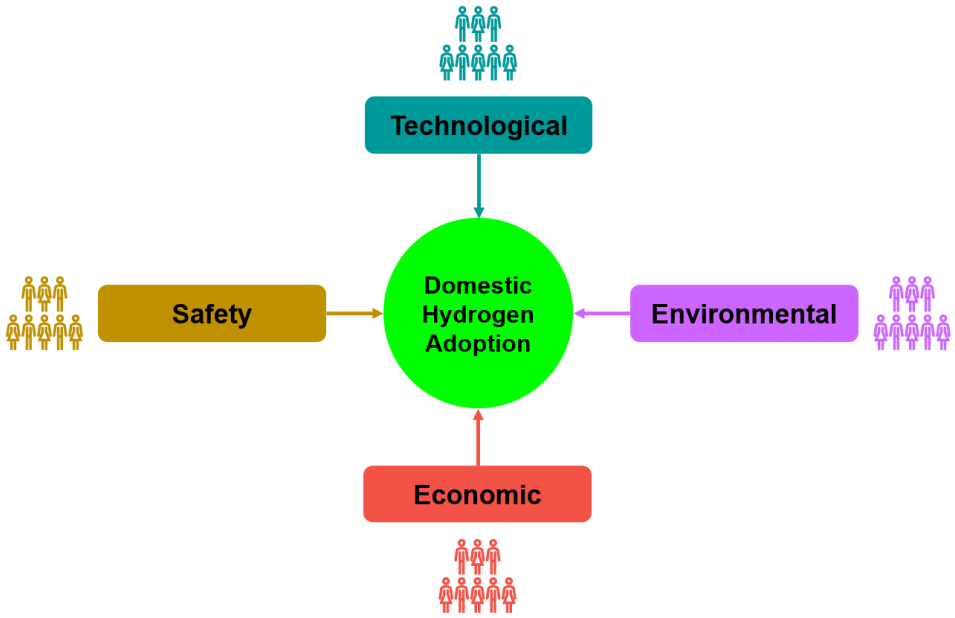
Keywords

Consumer acceptance; Consumer heterogeneity; Domestic hydrogen; Hydrogen production; Structural equation modelling; Technology adoption

Abstract

The UK Hydrogen Strategy (August 2021) and subsequent Heat and Buildings Strategy (October 2021) affirm that a strategic decision is set to be taken by 2026 on the prospect of residential decarbonisation via 'hydrogen homes'. As this decision date draws nearer, quantitative insights on consumer perceptions of hydrogen-fuelled heating and cooking appliances remain limited. The existing knowledge deficit presents a substantial barrier to implementing a socially acceptable deployment pathway for residential decarbonisation. Despite recent efforts to advance the social science research agenda on hydrogen acceptance, few studies have advanced theoretical knowledge or pursued comprehensive statistical analyses. This study responds to the extant research gap by analysing the adoption potential for hydrogen homes via partial least squares multigroup analysis. Drawing on data from a nationally representative online survey (N = 1845) conducted in the UK, the adoption dynamics for domestic hydrogen are compared across four sub-groups of the population. The findings suggest that non-economic constructs such as safety perceptions and production perceptions are potentially more influential at this stage of the domestic hydrogen transition. While non-economic constructs including technology perceptions explain differences between consumer sub-groups, financial perceptions are somewhat homogeneous across the segments. The intricacies of these findings are critically important to strengthening residential decarbonisation efforts through segment-specific polices and strategic engagement with consumers. Policy makers and key stakeholders should seek to factor consumer heterogeneity into net-zero decision-making processes, which entails acknowledging the potential amplifying effect of technology and environmental engagement in supporting residential decarbonisation. It emerges that consolidating community acceptance is a prerequisite to enabling the adoption of hydrogen homes appliances, following local trials and a prospective policy decision on the transition. Socially acceptable strategies for decarbonising the residential sector can be guided by insights on heterogeneous household preferences.

Graphical abstract



5.1 Introduction

Accelerating residential decarbonisation is critical to realising a net-zero energy future in the United Kingdom (UK) [1,2] and many countries around the world [3,4]; several of which share an oceanic climate, dependency on fossil fuels for heating, and targets for reducing greenhouse gas (GHG) emissions [5]. Currently, around 38% of the UK's natural gas demand is used for residential heating [6], which accounts for approximately 14% of national GHG emissions [7]. However, for several years, the residential sector has remained at the margins of system-wide decarbonisation efforts [8]; following a primary focus on phasing out coal power [9] and scaling up renewables to reduce emissions from the electricity sector [10].

Consequently, targets for decarbonising the housing stock have fallen short [11]; owing in part to prolonged consumer resistance towards low-carbon alternatives such as heat pumps [12,13] and inconsistent government strategies [2,14,15]. For example, in their recent systematic review of developments in national heat pump markets, which included a focus on the UK, Gaur et al. [13] identified a range of regulatory, economic, structural, and infrastructure barriers, in addition to issues of social acceptance.

At present, the UK government is exploring a range of technologies for supporting residential decarbonisation efforts [16]. As stated in the UK Hydrogen Strategy [17] and subsequent Heat and Buildings Strategy 2021 [16], the prospective technology portfolio [18,19] includes hydrogen-fuelled appliances for domestic space heating, hot water, and cooking [20–22]. Notably, the government recognises the potential for converting up to four million households to domestic hydrogen by 2035 [23]; should the use case be established following a series of demonstration projects [24,25] and local trials [26–28]. Within the wider context of establishing a national hydrogen economy to support net-zero [29], a policy decision on the role of hydrogen for domestic use is set for 2026 [17]. However, ahead of this decision and potentially 'critical juncture' [30] in the UK's energy future [31,32], researchers are yet to examine the role of consumer heterogeneity [33,34] in shaping potential market acceptance for 'hydrogen homes' [35,36].

To date, the scientific literature has focused primarily on techno-economic assessments of hydrogen production pathways [37,38], alongside models and

forecasts for the hydrogen economy [32,39,40]. Research on domestic hydrogen has followed a similar trajectory [7,41,42], employing tools such as the UK Times Model [32,43].[1] Although primarily concentrated on aspects such as network investments, fuel types, costs, and emissions [43], forecasters also recognise that factors such as demographics, social habits, public views towards heating, and underlying levels of acceptability will influence domestic energy demand and market developments [5,19]. Accordingly, early efforts have been taken to advance the social science research agenda on domestic hydrogen [44], as reflected by a recent uptake of largely qualitative studies [21,31,45,46]. However, as emphasised by Almaraz et al. [47], there is a growing need to report statistical data to demonstrate the validity and reliability of survey data, as researchers continue to advance quantitative methods and new survey instruments.

As articulated by Becker et al. [48], it is often unrealistic to assume that survey data in social science research can be treated as a homogenous sample representing a single population. As an illustrative case, pooling data for two categories such as gender would imply a homogenous population (i.e. male and female respondents), thus path coefficient estimates would fail to account for the underlying heterogeneity within the sample [49]. Similarly, researchers may explore other socio-demographic variables such as age. For example, Poortinga et al. [50][2] recently examined generational differences in relation to climate change engagement among the five named generation groups.[3]

To date, systematic analyses of consumer heterogeneity remain scarce in the energy technology acceptance literature [51], as documented in Section 5.3. To an extent, the deficiency of a multigroup focus (especially extending beyond two dimensions), reflects a persistent trend towards implementing ineffective, one-size-fits-all energy policies in different country contexts, such as China [51], South Africa [52], Austria [53], Denmark [54], the US [55], and the UK [56]. Notably, Roddis et al. [57] demonstrate the extent to which support for energy sources may vary across different regions of the UK (see Appendix 0), further motivating the need for segmentation-specific analyses [58,59]. The need to mitigate the risk the one-size-fits-all approaches

[1] For example, Calvillo et al. [43] modelled a scenario wherein hydrogen is used in just over 5% of UK households by 2035, before growing to 42% by 2040 and reaching 56.6% by 2050.
[2] The study applied first-generation regression techniques as opposed to structural equation modelling.
[3] i.e. Generation Z, Millennials, Generation X, Boomers II, Boomers I and older.

has also been emphasised in the field of medical research, where researchers are increasingly employing analytical algorithms to understand heterogeneity among patients [60].

Given that consumer decision-making processes can vary significantly across segments, overlooking heterogeneity in empirical studies may lead to bias results and invalid conclusions [61,62], which could misdirect energy policy making. It follows a more realistic and strategic understanding of market acceptance dynamics can be supported by internalising consumer heterogeneity into decision-making [63–65]. In response, this study aims to advance the empirical evidence base on consumer attitudes towards the domestic hydrogen transition in the UK context by employing multigroup analysis (MGA).

The study applies partial least squares structural equation modelling (PLS-SEM) to determine which factors influence adoption potential for hydrogen appliances. To overcome the limitations of prior research efforts [44,66,67] and minimise the risks of invalid recommendations [48,61], partial least squares multigroup analysis (PLS-MGA) is conducted to determine whether the adoption potential varies across different consumer segments [62,68,69] (see Section 5.6). As outlined in Section 5.2.1, the research design is composed of four consumer segments, which are distinguished according to their level of technology and environmental engagement, and socio-economic status.

Following this introduction, Section 5.2 firstly reports the research design and methodology as means for framing the MGA and underlying hypotheses, which are developed in Section 5.4 following a review of the literature in Section 5.3. Next, Section 5.5 proposes a conceptual framework for examining consumer heterogeneity in the context of domestic hydrogen adoption potential. Section 5.6 reports the results from PLS-MGA and importance-performance map analysis (IMPA), while Section 5.7 discusses the implications of the findings and potential sources of consumer heterogeneity. Finally, Section 5.8 concludes the study by outlining opportunities for advancing the social science research agenda on hydrogen homes [44].

5.2 Materials and methods

Research practitioners should follow up-to-date guidelines and adhere to best practices when employing PLS-SEM [70,71] and implementing PLS-MGA [62,72].

These complementary methods were employed systematically [49,62] throughout this analysis, as described in the following subs-sections. Firstly, Section 5.2.1 outlines the research design and sampling approach, before reporting the procedures for PLS-MGA in Section 5.2.2.

5.2.1 Research design and sampling approach

This study examines data collected through an online survey, which ran between October and December 2022. The survey aimed to collect information on consumer attitudes towards the domestic hydrogen transition in the UK context. The survey instruments were fine-tuned through literature review findings [35,36,73,74] and qualitative results from online focus groups [31,46,75], and further validated through pilot tests and inputs from academics (social scientists and hydrogen specialists). Qualtrics software [76] was employed to program the survey, with content and face validity established ahead of final deployment in October 2022. Full details of the survey questions, answers scales, and references to supporting literature are provided in Appendix 0 (see Table 0-1).

Notably, recent research has highlighted the place-specific dynamics of the UK domestic hydrogen transition, which sees deployment of hydrogen homes primarily targeted for the north of England in proximity to industrial towns [36]. In response, a nationally representative sample (N = 1845) was secured by implementing quotas for socio-structural variables (i.e. housing tenure, property type) and socio-demographic characteristics [77] (i.e. age, gender, income), in addition to a quota for location (see Table 0-2). The potential influence of respective socio-structural and socio-demographic variables [77] are explored in Section 5.7.

This study advances the literature by testing whether concern for climate change and other environmental issues, alongside engagement in renewable energy technology, in addition to fuel stress, are significant predictors of domestic hydrogen adoption potential. As described in Section 5.3.3, heterogeneous consumer preferences can shape prospects for technology adoption and impact the feasibility of low-carbon energy transitions. In response, four distinct sub-groups were targeted (see Fig. 5-1 and Fig. 5-2): a Moderately technology and environmentally Engaged Group (MEG); a Very technology and environmentally Engaged Group (VEG); a Fuel Stressed Group

(FSG) with less than moderate levels of technology and environmental engagement; and a Baseline Group (BLG) which filtered out all previous categories (see Table 5-1).[4]

Table 5-1. Consumer sub-groups composing the survey sample.

Sub-group	Consumer specifications
Moderately Engaged Group (MEG) N = 458	• Moderate level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Moderate interest and engagement in environmental issues • Not experiencing fuel stress
Very Engaged Group (VEG) N =331	• High level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Strong interest and engagement in environmental issues • Not experiencing fuel stress
Fuel Stressed Group (FSG) N = 379	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Living in fuel poverty or experiencing high levels of fuel stress
Baseline Group (BLG) N = 677	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Not experiencing fuel stress

Accordingly, this study contends that differences in technology and engagement levels, and socio-economic conditions, will influence consumer attitudes towards the domestic hydrogen transition [35,36,78]. The decision to introduce segmentation via technology and environmental engagement filters, in addition to fuel stress (see Table 0-2) provides an important continuum to recent research carried out in the UK [31,46,75], while significantly advancing prior engagement with the topic of hydrogen acceptance [66,79,80]. Specifically, Gordon et al. [31,46,75] laid the foundations for this approach by conducting ten online focus groups (N = 58), which compared a range

[4] As a result, the sampling approach increases national representativeness by combining a control group (i.e. the BLG) with three specific sub-groups.

of consumer segments, defined according to five categories: interest in renewable energy and joining a renewable energy community; ownership of solar PV panels and multiple smart home technologies; active engagement in environmental issues; facing fuel poverty or high levels of fuel stress; and living in an industrial city or town.[5]

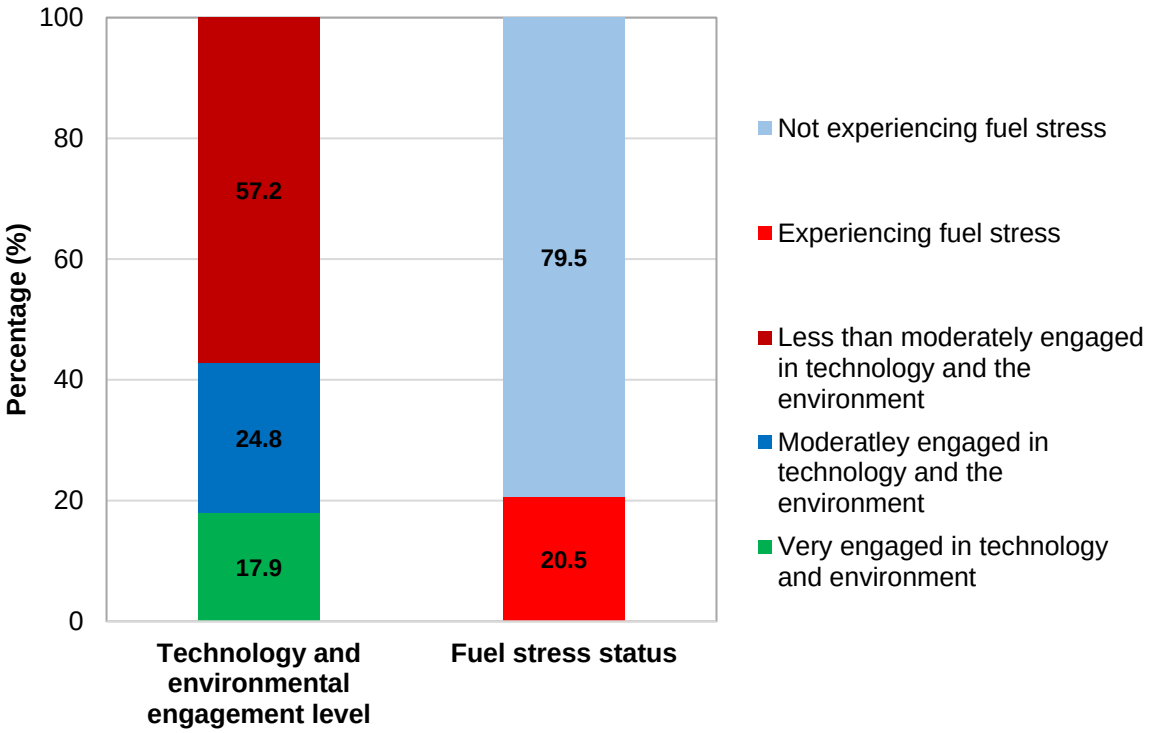


Fig. 5-1. Composition of consumer sub-groups by categorical filters.

The Fuel Stressed Group (FSG) is represented in red and accounts for 20.5% of the orange bar. The Baseline Group (BLG) represents the remaining 37.6% in the orange bar. The grey bar (79.5%) reflects the cumulative percentage of the BLG, Moderately engaged in technology and environmental Engagement Group (MEG = 24.8%), and Very engaged in technology and environmental Engagement Group (VEG = 17.9%).

[5] Likewise, the focus groups analysis carried out during this PhD project included a control group which filtered out other categories, in addition to differentiating between strong and moderate interest in renewable energy and joining a renewable energy community (see Appendix D–E).

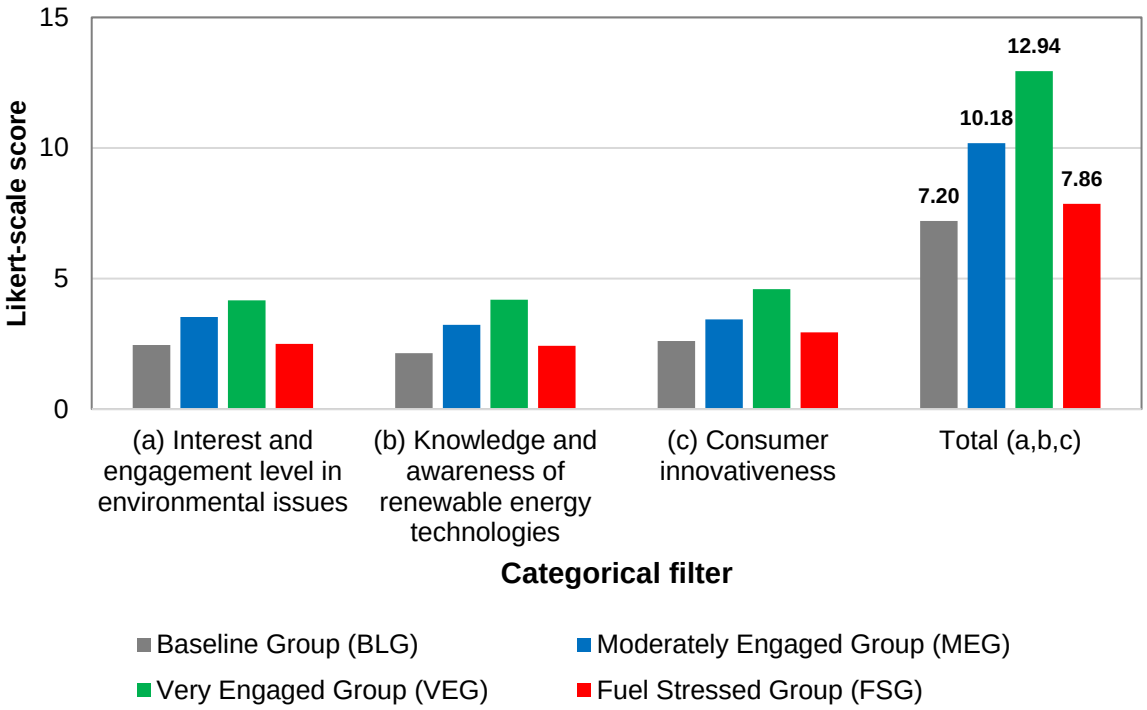


Fig. 5-2. Responses to filtering questions across consumer sub-groups

Following the research design, sample size requirements [81] are evaluated at the sub-group level [72] using statistical power tests [82,83], as illustrated in Fig. 0-2 and Fig. 0-3. With six predictor variables, one mediating variable, and one dependent variable, the smallest sub-sample in this study (N = 331) is sufficient to detect a moderate effect size (f^2 = 0.065) at a 95% significance level (ρ<0.05). Furthermore, the largest sub-sample can detect a smaller effect size (f^2 = 0.035), as indicated by G-Power software analysis [84,85].

To rule out the risk of common method bias (CMB) [86] in survey responses [87], Harman's single factor test was applied [88], which returned an overall variance significantly below the acceptable threshold of 50% (see Table 0-4). Additionally, following the method of Kock et al. [89], a random variable was generated to serve as the sole endogenous construct within each model, which returned variance inflation factor (VIF) scores below the threshold of 3.0 for each model [86]. Finally, no instances of skewness or kurtosis were present among the measurement items [83,90] since all values were between -2 and +2, suggesting the symmetry and distribution of the sample is appropriate for analysis in PLS-SEM [83,91].

5.2.2 Partial least squares multigroup analysis

PLS-SEM is a well-stablished research method [92,93] for measuring and analysing the relationship between observed and latent variables [94–96]. PLS-SEM is based on ordinary least squares regression, which calculates both the variance and covariances of variables to estimate regression coefficients [97]. Researchers employ the approach to test hypotheses within a conceptually-grounded path model [98].

Critically, PLS-SEM is the recommended approach when theoretical development is required and the focus is on exploration and prediction [69,99,100], as opposed to theory confirmation [101,102].[6] As a result, the technique has gained increasing traction among social scientists for advancing exploratory research [90,101] across a wide range of domains [62,92], such as smart energy technology adoption [103–105] and hydrogen acceptance [106–108]. In view of the need to advance theoretical understanding and empirical evidence [34,73] on domestic hydrogen adoption potential [21,45], this study undertakes PLS-MGA using SmartPLS 4.0 software [109].

Understanding the rationale of multigroup analysis (MGA) stems from recognising the role of moderators, which Frazier et al. [110] characterise as "addressing 'when' or 'for whom' a variable most strongly predicts an outcome variable." Thus, moderating variables are critical for assessing whether two variables share the same relation across groups [111,112]. In situations where the moderator is categorical (e.g. nationalities, gender etc.) and the goal is to test the moderation effect on the entire model (i.e. all structural paths), the recommended analytical technique is MGA [49,111]. PLS-MGA is an established method for efficiently testing moderation across multiple relationships in a structural model [62,113], thereby accounting for the presence of group-specific differences [114]. Thus, PLS-MGA functions by testing whether statistically significant differences exist between sub-groups, which the researcher identifies a priori during the sampling stage (i.e. BLG, MEG, VEG, FSG).[7]

PLS-MGA is conducted in six stages to examine whether the perceptions and behavioural intentions of different consumer sub-groups are heterogeneous in respect to domestic hydrogen appliances (see Fig. 5-3).The first stage involves defining how

[6] When models and hypotheses have been thoroughly developed, covariance based structural equation modelling (CB-SEM) can be applied for theory testing and confirmation [71]. The differences between CB-SEM and PLS-SEM are extensively documented in the literature and remain contested [97,101].
[7] This approach is distinct from a posterior approach wherein the research tests for unobserved heterogeneity within the data to identify the plausibility of different segments or 'clusters' [48, 61].

the groups are generated and specifying sample size requirements[8] for achieving statistical power, as outlined in Section 5.2.1. The second stage involves validating the measurement model through requisite checks for reliability and validity. Subsequently, the measurement invariance test of composite models (MICOM) procedure [115] is employed to determine whether group comparisons are feasible [116].

The first step of the MICOM procedure involves establishing configural invariance, whereby the constructs are equally parameterised and estimated between each sub-group [115]. Secondly, compositional invariance must be achieved by verifying that the "original correlation" is equal to or greater than the 5%, or by ensuring the *p*-value is non-significant. When both configural and compositional invariance are established, full measurement invariance (i.e. composite equality) is plausible, provided both the mean and variance of the "original differences" fall between the lower (2.5%) and upper boundaries (97.5%). Alternatively, partial invariance is established when none or just one of the mean values or original differences falls between the lower and upper boundaries [49,62,115].

Following the MICOM procedure, which satisfied the conditions for establishing at least partial measurement invariance (see Section 5.6.3), the differences between path coefficients for respective pairwise comparisons are analysed using available parametric and non-parametric tests [62] in SmartPLS 4.0 [109]. In cases where statistically significant group-specific differences are observed [115], the next step involves analysing the structural model for each sub-group, including an assessment of in-sample and out-of-sample predictive power. Subsequently, the modelling results are compared via an importance-performance map analysis (IMPA) [117,118] to identify areas of strategic importance for supporting consumer acceptance. In the final stage, the statistical findings are further explored by examining potential sources of consumer heterogeneity linked to socio-structural and socio-demographic variables.

[8] Nevertheless, many researchers fail to meet sample size requirements, such as the study of Murbarak and Petraite [361] which compared Malaysia (N = 124), Indonesia (N = 109), and Thailand (N = 91).

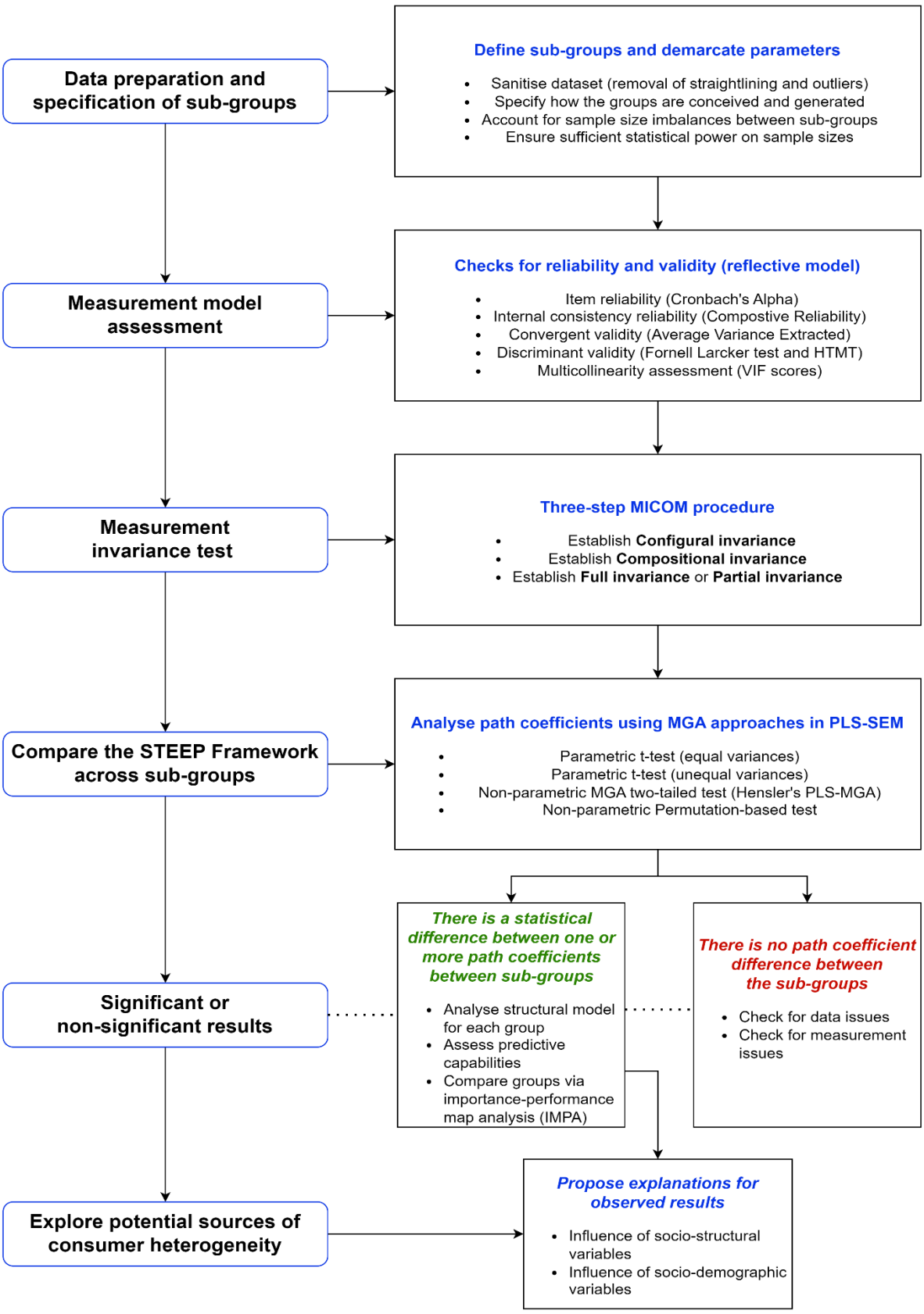


Fig. 5-3. Research procedure for performing PLS-MGA.

Source: Authors' design based on [49,62,115].

As an entry point into the PLS-MGA, descriptive statistics are firstly analysed using IBM SPSS Statistics 28.0 [119] to demarcate the adoption characteristics of each sub-group. Additionally, a series of Kruskal-Wallis (K-W) non-parametric H-tests [120] are conducted to compare willingness to adopt domestic hydrogen between consumer segments. This procedure supports the preliminary analysis ahead of more rigorous statistical analysis via PLS-MGA (see Section 5.6).

The K-W test provides an adaptation of classical one-way analysis of variance (ANOVA) [121,122] to compare the median ranks of more than two independent groups [123,124], wherein the null hypothesis (H_0) states that the median ranks of each group are the same [125]. However, the K-W test is not without its limitations, as outlined in Appendix 0. Overall, the novel methodology employed in this study reflects recent research efforts to combine a suite of PLS-SEM tools and complementary statistical approaches [126–128].

5.3 Literature review

5.3.1 Scopus search results on PLS-SEM and PLS-MGA

An entry point into this analysis is the recent review article of Cheah et al. [62] in the Journal of Business Research. The authors conducted a keyword search (article title, abstract, and keywords) on "PLS-SEM Multigroup Analysis"[9] in Science Direct and Scopus for the period 2010–2021, which returned 378 articles sourced from 183 journals [62]. The search results included 350 articles since 2017, with the highest frequency within the final year (N = 118). The principle finding of the search was to highlight the paucity of studies which analysed more than two groups [62]. Specifically, since 2017, one in five studies applied PLS-MGA to more than two groups.[10]

In view of findings of Cheah and colleagues [62], a Scopus search (article title, abstract, and keywords) for "PLS-SEM" AND "energy" was conducted, which returned 188 journal articles for the period 2017–2023. The results show a recent proliferation of PLS-SEM in energy studies, reflected by a five-fold increase since 2020. A subsequent search in Scopus targeted the following keywords in article title, abstract, and keywords: "PLS-SEM" AND "multigroup" OR "multi-group" AND "technology." The search returned 66 journal articles with sustained growth since 2021. Notably, filtering

[9] Including the following derivatives: "PLS-SEM Multigroup", "PLS-MGA", and PLS Multigroup".
[10] 2017 = 16.7%; 2018 = 21.6%; 2019 = 19.3%; 2020 = 18.2%; 2021 = 24.2%. Standard deviation for the period = 2.97.

the results by subject area in Scopus reflects a scarcity of PLS-MGA studies among energy researchers (N = 5),[11] whereas the fields of business, management, and accounting (N = 33), social sciences (N = 30), and computer science (N = 18) dominate the sample.[12]

The growth dynamics of PLS-SEM among energy researchers and the modest uptake of PLS-MGA in technology acceptance studies is captured in Fig. 5-4. Foremost, the initial exploration corroborates the comparative paucity of multigroup analyses within the PLS-SEM field [62], which mirror the wider literature in typically focusing on (two-group) comparisons between gender [129,130], age [50,65,131], income [132–134], or country [135,136]. Nevertheless, some researchers such as Kaur et al. [137] have responded by accounting for variables such as gender, income, occupation type, and education level when examining the green buying intentions of millennials in India. The study reported significant differences regarding the influence of monthly income and education level [137]. The importance of multiple socio-demographic variables has also been emphasised by Girod et al. [138], noting that willingness to adopt smart thermostats in Germany registered highest among young men with high savings potential (i.e. low apartment occupancy and high energy use) and a high income and education level.

To supplement and further validate insights related to multigroup analysis, an additional key word search was implemented in Scopus (article title, abstract, and keywords) for “multigroup analysis OR multi-group analysis” AND “structural equation modelling” OR “structural equation modelling” OR “SEM” OR “PLS-SEM,” which returned 1380 articles for the period 2012 to 2023 (see Fig. 5-5).[13] As displayed in Fig. 5-6, energy studies represent a small fraction of the sample (~3.2%), while multigroup analysis features somewhat more prominently in the environmental sciences (~6.1%), which is consistent with the results supporting Fig. 5-4.

[11] Seven studies corresponded to the field of environmental science.
[12] Notably, in their review of articles with PLS-SEM applications in Industrial Marketing Management Journal, Guenther et al. [324] retrieved 139 articles for the period 1998–2020, which mirrors the Scopus search results. Magno et al. [352] also retrieved 177 articles from eight quality management journals for 2003–2021, which reflected a doubling in outputs between 2020 (N = 15) and 2021 (N =30).
[13] 2012 and 2013 marked the first consecutive years where results exceeded 20 articles.

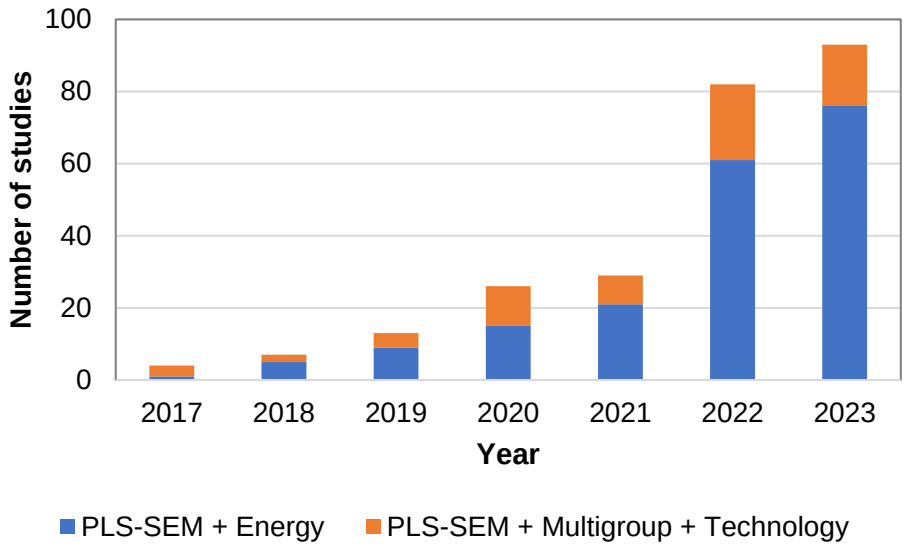


Fig. 5-4. Comparison between Scopus search results for PLS-SEM and PLS-MGA.

Following the Scopus search, Table 0-3 provides a summary of ten impactful studies which applied multigroup analysis across a range of areas, such as e-commerce [131,139,140], e-learning [141], and eco-purchasing wherein Barbarossa and De Pelsmacker [64] compared green consumers (N = 453) and non-green consumers (N = 473) in the Italian context [64]. Seminal contributions to the literature further reflect a constraint of two-group comparisons or a narrow focus on socio-demographic moderators such as gender and age, as reflected within the UTAUT [142].

Among numerous examples (see Section 5.3.2), scholars have also leveraged MGA to examine eco-friendly purchasing behaviour [136], intentions to purchase organic food [136], the antecedents of corporate social responsibility [143], and the role of agricultural education in the circular economy [144]. Additionally, researchers have employed MGA to investigate energy behaviours among rural residents [145], behavioural intention to ride in autonomous vehicles [146], adoption intention of battery electric vehicles [147], purchase intention for hydrogen automobiles [134], and purchase intention towards energy efficient appliances [148]. Against this background, the next sub-section undertakes a more targeted review of multi-group analyses within the field of energy technology acceptance, as a means for developing a series of testable hypotheses.

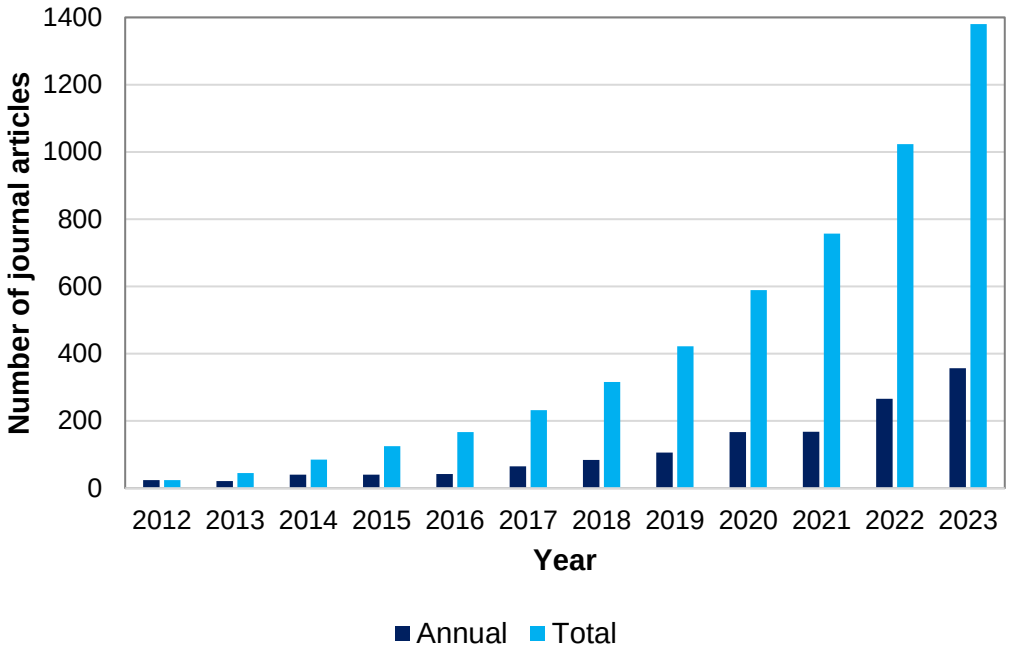


Fig. 5-5. Scopus search results for articles employing SEM-based multigroup analysis.

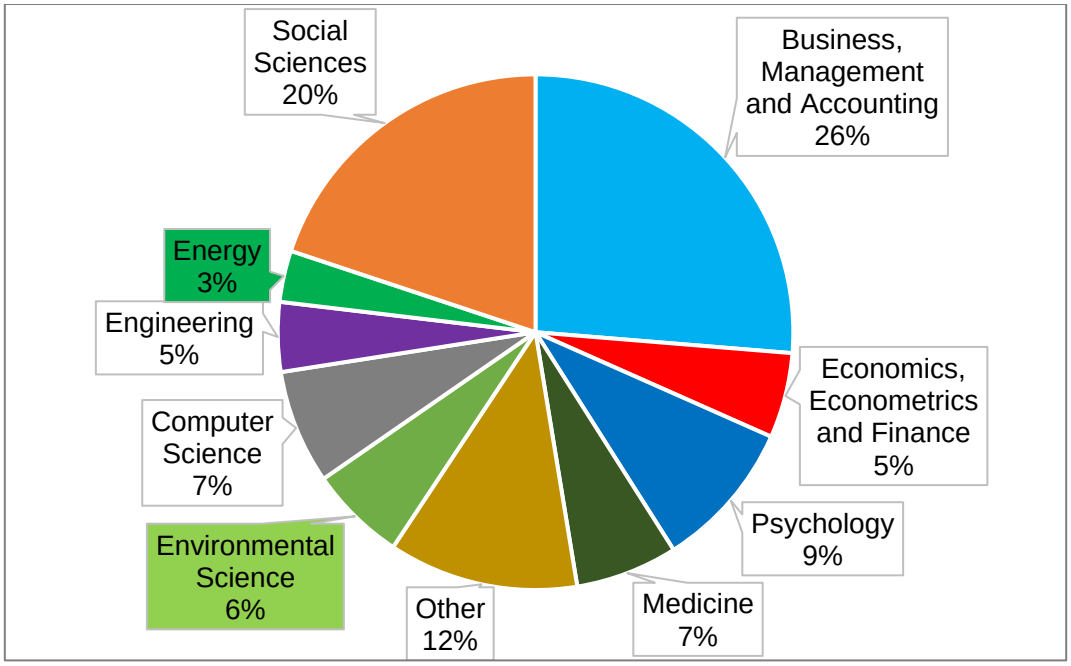


Fig. 5-6. Prevalence of studies using SEM-based multigroup analysis by research field.

5.3.2 International studies with a focus on consumer heterogeneity

The importance of consumer heterogeneity in decision-making for the energy transition has been highlighted in a range of country and technology contexts (see Appendix O). Motivated by the need to better capture the complexity of human behaviour in technology decision-making, McCollum at al. [63] advanced the

parameters of modelling consumer heterogeneity by representing 27 unique sub-groups in their global assessment of purchasing decisions for (low-carbon) light-duty vehicles[14] Critically, by accounting for heterogeneous non-monetary attributes, it was observed that the market penetration of electric vehicles may be delayed for several decades [63].

Subsequently, Desai et al. [55] constructed a model of personal vehicle preferences in the US, which suggested accounting for consumer heterogeneity would result in 23% higher market share for electric vehicles by 2040. Contrary to the findings of McCollum et al. [63], the results implied a possibility for "cascading diffusion" of electric vehicles within the US market over the next two decades, while underscoring the implications of accounting for both domestic and international heterogeneity when formulating energy policies [55]. The dual focus is critical during the formative stage, as niche markets develop and international learning curves drive prospects for domestic technology diffusion [149,150], such is the case with hydrogen energy technologies [151,152].

In the context of net-zero energy buildings in South Korea, Choi et al. [153] distinguished between 'forward-looking consumers', 'cost-sensitive consumers', and 'cost-insensitive consumers' to reflect heterogeneous preferences. Choi and colleagues [153] also reported the influence of socio-demographic factors on housing preferences, indicating the potential of "unobservable common determinants among individuals with similar characteristics." Based on the notion of heterogeneous strategic consumers introduced by Guo and Hassin [154], Liu et al. [155] further demarcate between strategic and homogenous (i.e myopic) consumers; analysing threshold scenarios in which strategic consumers opt for a low price, high 'greenness', or compare price and greenness before reaching a price threshold.

The notion of strategic and myopic consumer categories aligns to the inclusion of different levels of engaged (i.e. strategic) and non-engaged (i.e. myopic) consumers within this study. Notably, Liu and colleagues [155] reported that consumer heterogeneity influences the potential profitability of the low-carbon supply chain;

[14] Demarcated according to three dimensions: settlement pattern (urban, suburban, rural); adoption attitude (early adopter, early majority, late majority); and vehicle usage intensity (modest driver, average driver, and frequent driver).

underlining the need for effective subsidy schemes to support strategic consumer behaviour in promotion of supply chain sustainability.

Analysing the rebound effect in the Austrian context through a computable general equilibrium model, Kulmer and Seebauer [53] also emphasised the importance of accounting for household heterogeneity in view of divergent consumer preferences. Furthermore, based on survey data collected from 921 urban households in China, Lei et al. [51] illustrated how consumers have 'heterogeneous energy lifestyles', as reflected by different energy consumption habits and purchasing preferences for home appliances. In turn, the authors advocate for the notion of "common but differentiated household mitigation policies" to support the energy transition [51].

In the context of the hydrogen economy, a focus on intergroup comparisons remains primarily limited to early exploration in the UK [31,46,75] and Australian contexts [66,67]. Insights from large datasets are constrained to examining the effects of gender and political party preferences in the Australian context [67] (see Appendix 0). Although Bögel et al. [156] compared public attitudes towards hydrogen fuel cells across seven EU Member States, PLS-MGA is yet to be employed to derive more comprehensive findings on consumer heterogeneity at the national level.

5.3.3 Segmentation approaches and operationalisation of constructs in technology acceptance studies

In the early context of understanding internet use, personal innovativeness was defined by Agarwal and Prasad [157] as "the willingness of an individual to try out any new information technology" (206). Subsequently, measures related to consumer innovativeness have proved significant in predicting early adoption potential for emerging technologies. For example, Aldas-Manzano et al. [158] found that consumer innovativeness increased internet banking use among Spanish customers while also reducing risk perceptions. In India, consumer innovativeness positively moderated both behavioural intention and adoption readiness among users and non-users of mobile payment services [140]. Among Malaysians, consumer innovativeness had a significant effect on perceived usefulness and perceived ease of use regarding wireless internet on mobile devices [159], with the same relationship also observed for consumer acceptance of a home energy management system in South Korea [103]

Different aspects of customer innovativeness have also been associated with consumer preferences for electric vehicles in the United Kingdom [160] and China [161], as well as e-bikes and e-scooters in Scandinavia [162], in addition to predicting the adoption of sustainable household technology in the United States [163]. A recent study further demonstrated that consumer innovativeness positively moderates attitude towards adopting solar PV and adoption intention in Vietnam [164], while also proving a significant factor for consumer acceptance in Iran [165] and adoption intention in Taiwan [166].

Moreover, Lozano et al. [66] observed a positive association between Australian respondents who describe themselves as 'innovators' or 'early adopters' of new technologies and support for hydrogen. Specifically, the innovator group had an expressed preference for adopting hydrogen appliances for space and hot water heating [66]. To better understand the energy transition dynamics in the Chinese context, Wang and colleagues [167] used structural equation modelling to test the following hypothesis: for different innovation segments (earlier adopters, mid-term adopters, and late adopters),[15] attitude, subjective norms, perceived behavioural control, altruism, and community identity will influence intention to participate in renewable energy communities. The study affirmed the importance of formulating segment-specific strategies to increase participation prospects for each group in support of the renewable energy transition.

Traditionally, researchers operationalise aspects such as environmental knowledge as an exogenous construct, as applied by Park [168] to examine the social acceptance of green electricity among South Koreans. Specifically, the study of Park [168] asked respondents (N = 1239) about their familiarity with and knowledge about green electricity (EK1 and EK2), and their knowledge about energy and the environment (EK3). While environmental knowledge had an insignificant effect (β = 0.008) on acceptance of green electricity among South Koreans [168], Harichandan and Kar [80] reported a significant positive effect (β = 0.212) between environmental concern (4 indicators) and attitude towards hydrogen fuel cell vehicle adoption in India (N = 441). The example highlights the discrepancy between different approaches to measuring

[15] Segmented via an agglomerative clustering method.

environmental perceptions, while drawing attention to potential cross-cultural differences, which may motivate MGA when examining similar research questions.

Although the literature highlights the need to account for different segments of the population [169,170] when considering the adoption of low-carbon energy technologies [127,171–173], multigroup analyses on energy technology acceptance remain narrow. Studies tend to employ an environmentally conscious group for comparative purposes, as noted by Meng et al. [174] when reviewing consumer heterogeneity in the context of green supply chain development. Notably, Atasu et al. [175] divided consumers into 'primary' and 'green', wherein the environmentally conscious (green) segment valued product functionality as opposed to newness.

In distinguishing between 'traditional' and 'environmental' consumers, the study of Sarkar and Bhadouriya [176] suggested that an increase in the share of environmentally engaged consumers would lead to improvements in the green quality of manufactured products. Similarly, in examining the market for 'new energy vehicles', Gong et al. [177] differentiated between 'ordinary' and 'green consumers', showing that the presence of low-carbon preferences has implications for supply chain profitability.

Examining drivers of household adoption of energy efficiency smart solutions in Romania (N = 302), Popa et al. [178] compared two categorical variables, namely, age (less than or more than 30 years) and income level (monthly income less than or more than 2000 RON). The income variable was designed to account for vulnerable consumers, which aligns to the rationale of sampling a fuel stressed group of respondents within this study. Lie et al. [51] further highlight the limitation of most prior studies, which classify households by a single dimension such as income or age [50], as opposed to internalising multiple socio-structural characteristics [77].

Applying PLS-MGA to a novel context, Alomari et al. [179] observed that faculty members in Kuwait demonstrate a more positive intention towards energy conservation compared to students and staff, which is explained by higher levels of environmental knowledge and awareness of environmental consequences. Additionally, analysing the market for air conditioners and refrigerators, Shen and Saijo [180] conclude that rising environmental awareness among Chinese consumers in Shanghai may drive the adoption of energy efficient appliances [180]. Furthermore,

Parkins et al. [181] found that public engagement in energy issues had a significant positive effect on adoption intention for solar PV among Canadians, whereby stronger engagement is also positively associated with higher self-perceived knowledge of the energy system.

In turn, this study employs PLS-MGA to comprehensively examine the scope for developing segment-specific policy strategies to support the domestic hydrogen transition. Following the literature review findings, different levels of technology and environmental engagement, in addition to socio-economic status, are operationalised into the modelling approach.

5.4 Hypotheses development

5.4.1 Safety Perceptions

Based on a systematic review of 65 documents on the hydrogen economy since 2000, Almaraz and colleagues [47] found that only 14 studies engaged with (technological) safety,[16] which was the lowest ranking of 12 identified social aspects. This level of under-exploration is surprising given that safety is a prerequisite to both technical feasibility and public support [47,182], which justifies the inclusion of safety perceptions in hydrogen acceptance studies (see Table 5-2). Other literature review results suggest safety perceptions will shape prospects for the domestic hydrogen transition [73], ranking as a 'significant' factor when compared to 13 other acceptance indicators [35]. Interestingly, among Dutch respondents, males had a higher perception of safety risks associated with flammability [183], suggesting potential divergence between genders or sub-groups of the population (i.e. technology engaged citizens).

Public perceptions of hydrogen safety may hinge firmly on mainstream media reports [184], which can sometimes skew towards a negative social representation [185], whereby explosive and catastrophic imagery [186] may permeate the public imagination [187–189]. Relatedly, in the wider context of energy issues and climate change, Stoutenborough and Vedlitz [190] observe how public perceptions of risk are often confined to media-constructed parameters. This study seeks to mitigate perception bias by asking respondents to evaluate the safety of hydrogen in

[16] Defined by the authors [47] as "the condition of being protected from or unlikely to use danger, risks, or injury while producing, transporting, storing, distributing or using hydrogen products."

comparison to natural gas, which mirrors the notion that “public participation is needed to guarantee a fair and transparent evaluation of hydrogen vs other fuels” [47].

Beyond the constraints of media-constructed parameters [190], Beasy et al. [189] argue that technical knowledge can support positive perceptions of hydrogen safety to support social acceptance [189]. However, the ability to access or absorb technical information may be constrained by opportunities for directly experiencing hydrogen technologies [191,192], and may diverge according to a range of socio-structural variables such as education level [193]. Such dynamics give rise to potential divergence regarding safety perceptions, as documented in mixed-method analyses on hydrogen acceptance [34,46].

The prospect of transitioning to hydrogen homes may elicit concerns over safety risks [21,46], which could provoke feelings of fear and dread, as observed with other hydrogen energy technologies such as fuel cell vehicles and fuelling stations [107,194,195]. Qualitative responses in the UK context highlight a mix of fears and discomfort [34,186], attributed primarily to the flammable nature of hydrogen gas [196]. In extreme instances, consumers associate hydrogen with nuclear power, citing disaster and devastation as the common denominator [34,197].

Despite its risk profile, hydrogen also presents some benefits such as the elimination of carbon monoxide poisoning in the residential environment [198]. Interestingly, evidence suggests that consumers with a high level of technology and environmental engagement may be more attuned to both the safety risks and benefits of domestic hydrogen [34]. Nevertheless, underlying risk perceptions [44,199,200] may prevent consumers from undertaking more in-depth safety evaluations, which threatens to constrain domestic hydrogen acceptance. Safety perceptions of gas-based and electric-powered cooking technologies may also diverge [21,67]. Accounting for the foreseeable influence of safety perceptions on prospects for deploying hydrogen homes (see Table 5-2), the following hypotheses are developed:

H1a: Safety Perceptions (SP) will significantly influence domestic hydrogen adoption potential across consumer sub-groups of the UK population.

H1b: Consumer sub-groups of the UK population will have heterogenous safety perceptions of domestic hydrogen.

Table 5-2. Summary of findings on safety perceptions of domestic hydrogen.

Study and year	Country context, sample size and methods	Key findings
[201] 2019	• United Kingdom • N = 39 • In-person Focus Groups	• Respondents felt assured that stringent safety standards would be enforced prior to approving the use of hydrogen in domestic settings, which instilled a sense of confidence
[44] 2020	• United Kingdom • N = 700 • Online survey • N = 102 • Paper survey	• Most online survey respondents perceived the impact of hydrogen homes appliances on safety to be neutral (68.9%), followed by positive (17.3%), and negative (13.9%) • Paper survey respondents were more equally split between a neutral (57.4%) and positive perception (34.7%), while a minority of respondents expressed a negative perception of hydrogen safety (7.9%)
[21] 2020	• United Kingdom • N = 100 • Paper survey	• Safety risks were perceived to be significantly higher in the kitchen setting • Gas hobs were seen to permeate domestic energy cultures, in view of their more tangible socio-material qualities compared to 'out-of-sight' gas boilers
[66] 2022	• Australia • N = 2785 • Online survey	• Respondents expressed high levels of trust (*M* = 4.11, *SD* = 0.92) that adequate safety precautions would be put in places to keep risks under control should a national hydrogen economy develop (as measured via a five-point Likert scale)
[46] 2023	• United Kingdom • N = 58 • Online focus groups	• Respondents expressed more confidence in the safety credentials of induction hobs as opposed to gas hobs • Safety assurances in the context of hydrogen cooking may prove critical to fuel stressed households, especially when composed of young families
[34] 2023	• United Kingdom • N = 1064 • Online survey	• Safety risks (N = 64) were cited 4.5 times more frequently than safety benefits (N = 14), while other respondents expressed a more neutral perception (N = 26)

5.4.2 Technology Perceptions

The performance aspects of new energy technologies such as hydrogen fuel cell vehicles [191,202,203] must be viewed favourably to accelerate the low-carbon energy transition [204]. Several contributions to the literature document the importance of technology performance as a driver of market adoption [205–208], however, few studies have analysed consumer perceptions regarding the functionality of hydrogen boilers and hobs (see Table 5-3). By contrast, other acceptance constructs such as

environmental perceptions and perceived risks have received significantly more attention in wider studies on hydrogen acceptance [73].

The importance of brand familiarity has been emphasised for consumer durables such as such as heating, ventilation, and air-conditioning appliances [209] and appears a relevant factor in the context of hydrogen home appliances [75], as detailed in Table 5-3. However, a wider evidence base highlights the critical importance of perceived technology attributes [210] across a wide range of products [211,212] and national contexts [213], such as solar PV adoption in the Netherlands [214], energy efficiency lighting in Malaysia [215], and smart home technologies in the US [163]. Crucially, sustainable energy technology acceptance in the residential context is higher when performance benefits are easily discernible [216], underscoring the need for hydrogen appliances to demonstrate a relative advantage over existing boilers and hobs [73].

Notably, research suggests that consumers with high innovativeness are more likely to derive satisfaction from adopting new energy technologies such as smart thermostats [138]. Moreover, Lozano et al. [66] reported a positive association between self-perceived early adopters of energy technologies (i.e. 'innovators') and hydrogen acceptance. In the Chinese context, Zha et al. [217] identified four specific consumer segments which should be accounted for when targeting policy interventions to accelerate technology diffusion for energy efficient appliances. Critically, respondents belonging to the lowest income group, which can be taken as a proxy for fuel stressed, attributed most importance to energy efficiency and had the highest tendency for energy conservation in view of potential cost savings. However, research conducted in the UK [21,44,46] is yet to substantiate whether such a finding may transmit to the context of hydrogen homes.

It is also conceivable that technology perceptions may vary according to appliance type (see Table 5-3), as reported in the case of energy efficient air conditioners and refrigerators in India [218]. Examining consumer acceptance for energy efficient refrigerators and washing machines, Zha et al. [217] highlighted the need to evaluate other appliances including cooking technologies (e.g. rice cookers in China) for deeper comparative insights. Notably, a recent narrative literature review ranked the lived experience of hydrogen cooking as a potentially 'major'[17] factor among other social

[17] The study employed five categories of importance: *critical, major, significant, moderate, minor* [35].

acceptance constructs, whereas the lived experience of hydrogen heating ranked as a ‘minor’ factor [35], in line with the study of Scott and Powells [21].

Qualitative results from one UK study highlighted potential divergence in consumer perceptions towards hydrogen heating and cooking technologies [46]. Nevertheless, respondents demonstrated similar levels of adoption potential when answering poll questions on a five-point Likert scale [46], which also proved the case in the Australian context [66]. In view of the need to comprehend technology perceptions at the early stage of the hydrogen transition, this study also accounts for perceptions towards hydrogen cooking appliances [46], which has remained largely overlooked in prior research due to a primary focus on hydrogen boilers [45,219,220]. The following hypotheses are formulated, as supported by the inclusion of a reflective-formative construct[18] in the proposed model [92]:

H2a: The perceived performance of hydrogen boilers (BLR) will positively influence domestic hydrogen adoption potential across consumer sub-groups of the UK population.

H2b: The perceived performance of hydrogen hobs (HOB) will positively influence domestic hydrogen adoption potential across consumer sub-groups of the UK population.

H2c: Technology Perceptions (TP) related to appliance performance will positively influence domestic hydrogen adoption potential across consumer sub-groups of the UK population.

H2d: Consumer sub-groups of the UK population will have heterogenous perceptions of hydrogen boiler performance.

H2e: Consumer sub-groups of the UK population will have heterogenous perceptions of hydrogen hob performance.

H2f: Consumer sub-groups of the UK population will have heterogenous technology perceptions of domestic hydrogen.

[18] Higher order constructs can support theoretical parsimony and reduce model complexity [362].

Table 5-3. Summary of findings on technology perceptions of domestic hydrogen.

Study and year	Country context, sample size and methods	Key findings
[221] 2018	• Australia • N = 2785 • Online survey	• Female respondents registered higher levels of concern over risks associated with changes to the 'lived experience' of cooking
[44] 2020	• United Kingdom • N = 700 • Online survey • N = 102 • Paper survey	• Most online survey respondents perceived the impact of hydrogen homes appliances on energy performance to be neutral (63.1%), followed by positive (32.3%), and negative (4.6%) • Paper survey respondents were more equally split between a neutral (50.0%) and positive perception (45.1%), while a minority of respondents expressed a negative perception of hydrogen safety (4.9%)
[66] 2022	• Australia • N = 906 • Online survey	• Consumers reported the same level of support for using hydrogen for cooking, as for space heating (*M* = 3.60) • Support for using hydrogen for hot water proved marginally higher (*M* = 3.71), as measured on a five-point Likert scale
[46] 2023	• United Kingdom • N = 58 • Online focus groups	• Consumers either believed or hoped that hydrogen appliances should offer an upgrade in terms of efficiency and smartness
[75] 2023	• United Kingdom • N = 58 • Online focus groups	• Product performance and product range ranked among the top tier variables behind preferences for buying an established brand
[78] 2023	• United Kingdom • N = 1064 • Online survey	• Performance benefits (i.e. efficiency or utility benefits) of hydrogen appliances ranked eighth out of 17 positive sub-factors of domestic hydrogen acceptance • Performance benefits (N = 35) were cited four times more frequently than performance losses (N = 9), and cited most frequently by respondents with a high level of technology and environmental engagement

5.4.3 Financial Perceptions

The broader literature on hydrogen energy acceptance [222,223], including studies on hydrogen fuel cell vehicles [224], highlights the importance of economic factors [225] and associated financial perceptions [222,223]. These observations are consistent with studies on low-carbon energy technologies, which find financial factors to be a critical barrier to consumer acceptance [226], as highlighted in the context of residential decarbonisation in the UK [227]. For example, it is well documented that

cost factors remain a critical barrier to deploying domestic micro-generation technologies to support residential decarbonisation [228,229].

Affordability concerns associated with transitioning to domestic hydrogen appliances have been recorded prior to the cost-of-living crisis [169,230], while follow-up work suggests financial costs rank as a 'critical' acceptance factor [35]. Given existing constraints on household finances, Thomas et al. [220] assert that social resistance is likely to arise if residential decarbonisation leads to a rise in UK energy bills. Similarly, Calvillo et al. [43] concluded that policy makers would need to ensure that the costs of hydrogen are comparable to gas for incentivising consumer adoption.

Divergence in financial perceptions has been documented in a recent study with online focus groups in the UK (N = 58). Foremost, fuel stressed respondents were cautious of hydrogen leading to a further hike in energy bills, which was viewed untenable even if motivated for long-term environmental and energy security purposes [75]. Relatedly, the risk of household energy vulnerability has been stressed in the context of Australia's domestic hydrogen transition [45]. By contrast, environmentally conscious UK citizens emerged as an outlier, instead conveying a degree of willingness to pay higher bills in promise of a greener (hydrogen) future [75], which supports other findings [31,231]. It follows that adverse macro-economic conditions could significantly stifle prospects for transitioning to hydrogen homes.

Based on a comprehensive typology identifying 48 specific factors of domestic hydrogen acceptance via qualitative coding, perceived *financial risks* ranked third in terms of explaining variance between consumer sub-groups [34]. Critically, evidence shows that concerns are strongest among baseline and fuel stressed respondents [34,75]. It follows that consumers may have divergent financial perceptions according to their socio-economic circumstances, as well as their environmental beliefs. Recent studies conducted in China [51,155] further highlight the relevance of interactions between consumer heterogeneity and market acceptance [232,233]. For example, Lei et al. [51] found that distinct household groups, clustered by income and age, have different sensitivities to the same energy policies, which influences purchasing preferences for air-conditioners. Additionally, Liu et al. [155] describe how 'strategic' consumers may delay their purchasing decisions for new technologies in anticipation of potential cost savings as the market develops.

In addition to informing the dynamics of market acceptance for hydrogen homes [35,36], insights on financial perceptions can help support wider national energy transitions [150,234] by supporting the evidence base on willingness to pay for green energy technologies [235,236]. In response, the following hypotheses are proposed to examine the influence of financial perceptions (see Table 5-4) and the potential for heterogeneous decision-making:

H3a: Financial Perceptions (FP) regarding the purchasing and running costs of hydrogen homes appliances will negatively influence domestic hydrogen adoption across consumer sub-groups of the UK population.

H3b: Consumer sub-groups of the UK population will have heterogenous financial perceptions of domestic hydrogen.

Table 5-4. Summary of findings on financial perceptions of domestic hydrogen.

Study and year	Country context, sample size and methods	Key findings
[227] 2023	• United Kingdom • N= 1551 • Online survey	• In Winter 2022, the government's Public Attitudes Tracker (PAT) reported concerns about the cost of installation (45%) as the main barrier to changing to a low carbon heating system • Concerns about running costs were cited by 25% of respondents
[237] 2019	• United Kingdom • N = 742 • Online survey	• Affordability concerns represented the most significant barrier to domestic hydrogen adoption for citizens living in socio-economically deprived areas of the North of England
[75]	• United Kingdom • N = 58 • Online focus groups	• Few consumers expect hydrogen appliances would be cheaper to purchase compared to traditional boilers and hobs • The wider majority are somewhat optimistic that price parity might be delivered which was also broadly the case for energy bills, whereas around one-third of respondents predict higher costs
[66]	• Australia • N = 906 • Online survey	• Respondents had a neutral perception of willingness to pay for the use of hydrogen technologies (*M* = 3.089, *SD* = 1.008) as measured on a five-point Likert scale
[34] 2023	• United Kingdom • N = 1845 • Online survey	• Perceived *financial risks* ranked as the third most critical factor, whereas perceived *financial benefits* ranked 28th among 48 sub-factors

5.4.4 Perceived Socio-economic Costs

The implications of the current energy crisis [238,239] and associated cost-of-living crisis [230,240] – including potential ramifications for domestic energy futures in countries such as the UK [169,241] – are far-reaching. Nevertheless, public

perceptions of energy technologies such as hydrogen are seldom contextualised within the broader socio-economic context [74]. Almaraz et al. [47] found that socio-economic factors were explored in just one-third of retrieved studies on social aspects of the hydrogen economy, while Scovell [223] and Dumbrell [242] emphasised the need to account for perceived socio-economic costs in hydrogen acceptance studies. This notion is also reflected in the broader literature on technology acceptance [243], including studies on domestic energy technologies such as solar PV and smart homes [73].

Prior to the cascading effects [239,244] of the COVID-19 pandemic [245,246] and ongoing Russo-Ukrainian War [247,248], survey results from the North of England (N = 700) suggested residents had a mostly neutral perception of socio-economic impacts related to the hydrogen switchover [44]. More recent longitudinal data from the PAT underlines the extent to which public concerns over energy insecurity and fuel stress prevail in the wider UK context [249]. Post-pandemic hydrogen studies conducted in the UK [34,75] also flag significant concerns of energy injustice [250,251], principally distributional [252,253] and procedural injustice [254,255]. For example, following online focus groups, energy justice concerns were cited most frequently by fuel stressed participants and citizens with a high level of environmental engagement [75].

Moreover, subsequent evidence suggests concerns over fairness and equity strongly influences the dynamics of domestic hydrogen acceptance [34]. Critically, worries related to a potential choice deficit concerning the transition to hydrogen homes registered highest among fuel stressed respondents [34]. By contrast, the same variable failed to register for consumers with the highest level of technology and environmental engagement [34]. Similar dynamics were observed when considering the impact of domestic hydrogen on the cost-of-living crisis, suggesting degrees of consumer heterogeneity towards perceived socio-economic costs [34].

In July 2023, the UK Minister for Energy Efficiency and Green Finance, Lord Callanan, announced the cancellation of a planned trial for hydrogen homes in Whitby village (Northwest England) [256], following local resistance and concerns over a lack of community benefits [257,258]. A lack of social acceptance likely reflects associated socio-economic concerns at the macro-level, as communicated by communities in the

North of England [44] and reinforced by fuel stressed respondents living in industrial towns [75]. Notably, approximately 10.3% of the Whitby population experience fuel poverty [259], while the surrounding area of Ellesmere Port ranks within the top 8% most deprived areas in England, according to the 2019 English Indices of Deprivation (IoD) [260]. Subsequently, amid further controversy, a proposed trial for Redcar (Northeast of England) was rejected in December 2023, casting doubt over the role of hydrogen homes in residential decarbonisation [261,262].

Although potential socio-economic benefits are envisioned by the UK government in terms of job growth and generation of gross value added from the hydrogen economy [17], which may trickle down to local communities [263], the current economic climate is mostly shrouded in instability and pessimism [264,265].[19] Against this backdrop, it is evident that consumer perceptions will prove context-dependent and place-specific. In response, this study explores how consumers perceive potential socio-economic risks related to national energy insecurity and fuel poverty, which are explored through two hypotheses focused on perceived socio-economic costs:

H4a: The Perceived Socio-economic Costs (PSC) of transitioning to hydrogen homes will negatively influence domestic hydrogen adoption potential across consumer sub-groups of the UK population.

H4b: Consumer sub-groups of the UK population will have heterogenous perceptions of the socio-economics costs (PSC) of transitioning to hydrogen homes.

5.4.5 Production Perceptions

Research shows that public perceptions of specific energy technologies can vary significantly between countries [266] and at the sub-national level [57]. For example, Doran et al. [266] found energy efficient appliances and energy efficient houses were viewed relatively favourably by both German (N = 142) and Norwegian students (N =106),[20] whereas carbon capture and storage (CCS) received less support (Germany: *M* = 4.48; Norway: *M* = 5.67), which may infer opposition to ‘blue’ hydrogen (i.e. steam methane reformation with CCS) [31].

Focusing on onshore wind power, Gölz and Wedderhoff [267] applied PLS-MGA to compare social acceptance at the sub-national level (N = 2009), with Southern

[19] By contrast, the Australian public has a more positive outlook towards potential economic and energy security benefits from the hydrogen economy [66,79,189] in view of the country’s significant export potential to markets such as Japan and South Korea [363,364].
[20] German response: *M* = 6.01, *M* = 6.54; Norwegian response: *M* = 6.36, *M* = 6.95.

Germany presenting the highest rate of rejection to onshore wind turbines, whereas acceptance was strongest in Northern Germany. In the UK context, based on analysis of national survey data collected between 2012 and 2018, Roddis et al. [57] demonstrated that solar energy received the highest acceptance level (*M* = 80.1), followed by renewable energy in general (*M* = 76.8), whereas nuclear (*M* = 37.1) and fracking (*M* = 22.1) received the lowest approval rates.

Reviewing international evidence on public perceptions of energy transition pathways [266], alongside emerging evidence on hydrogen production technologies [268,269] and perceived environmental benefits [34], is instructive to the case at hand. Specifically, the UK government is targeting a 'twin-track' production approach, which aims to leverage benefits from a blue pathway, alongside a renewable-based (i.e. green) pathway using electrolysis [17]. To date, one small-sample study (N = 58) has engaged directly with this area, showing 39% and 46% of respondents to be very and somewhat supportive of the twin-track strategy, respectively [31]. However, it emerged that environmentally engaged citizens were more likely to question the credentials of blue hydrogen [31], mirroring critiques in the scientific literature [270–272]. Consequently, the twin-track approach was least supported among environmentally engaged respondents, whereas fuel stressed participants living in industrial towns expressed the highest level of support, in hope of a more secure and sustainable energy future [31]. Additionally, engagement in renewable energy technology strengthened support for the twin-track strategy [31].

Subsequent research found that environmental benefits were cited more frequently among fuel stressed respondents compared to the baseline group, inferring a higher degree of optimism for a clean energy future [34]. This pattern may reflect the high propensity for old and inefficient boilers within fuel poor homes, which raise concerns over environmental impacts, as well as safety and costs [46]. For example, in the case of Whitby village and the surrounding region of Ellesmere Port, it is documented that over 80% of homes an Energy Performance Certificate (EPC) rating between D–G [259], which may motivate interest in securing efficiency gains and environmental benefits.

Overall, the international literature (see Table 5-5) strongly supports the notion that support for green hydrogen production will trump other pathways [66,263,269,273],

and may be coupled to perceptions of synergistic benefits for cross-sectoral decarbonisation [274,275]. Nevertheless, a recent Japanese study underscored the potential for divergent attitudes in view of economic impacts, whereby 55% of respondents (N = 2880) preferred cheaper grey hydrogen production compared to the green alternative (45%) [268]. Against this rich background, two additional hypotheses are examined to extend the scope of inquiry:

H5a: Production Perceptions (PP) will significantly influence domestic hydrogen adoption across consumer sub-groups of the UK population.

H5b: Consumer sub-groups of the UK population will have heterogenous production perceptions (PP) of transitioning to hydrogen homes.

Table 5-5. Summary of findings on production perceptions of domestic hydrogen.

Study and year	Country context, sample size and methods	Key findings
[263] 2019	• United Kingdom • N = 578 • Online survey	• Respondents expressed a stronger preference for green hydrogen over blue hydrogen, as reflected by mean scores of 82/100 and 59/100
[44] 2020	• United Kingdom • N = 700 • Online survey • N = 102 • Paper survey	• Most online survey respondents perceived the impact of hydrogen homes appliances on the environment to be positive (69.9%), or otherwise neutral (26.6%) • Paper survey respondents had similar perceptions, split between 69.3% positive, 23.8% neutral, and 6.9% negative
[66] 2022	• Australia • N = 2785 • Online survey	• Respondents expressed higher levels of support for producing hydrogen from renewable energy and electrolysis only (*M* = 3.63, *SD* = 0.82), • Support for using fossil fuels with CCS as an intermediate step while transitioning to renewables was comparatively lower (*M* = 3.18, *SD* = 0.91) • Respondents partially agreed that hydrogen contributed to climate change protection (*M* = 3.51, *SD* = 0.85), as measured on a five-point Likert scale
[269] 2023	• Norway • N = 1906 • Online Survey	• Norwegian citizens favoured green hydrogen (*M* = 3.90) over blue hydrogen (*M* = 3.20) and grey hydrogen (*M* = 2.30), as measured on a five-point acceptance scale
[34] 2023	• United Kingdom • N = 1064 • Online survey	• Respondents with moderate and high levels of technology and environmental engagement made most references to environmental benefits
[276]	• Germany • N = 2054 • Online survey	• Respondents expressed openness towards local use of green hydrogen, with strong expectations for environmental benefits

5.4.6 Adoption potential

Perceived benefits plays a prominent role in technology acceptance models, typically acting as an antecedent of attitude toward to use, as conceptualised within the TAM vis-à-vis perceived usefulness [277]. Focusing on the hospitality sector, Wang and Qualls [278] adapted the TAM to examine the relationship between perceived ease of adoption, perceived benefits of adoption, and technology adoption behaviour, wherein perceived benefits also acted as a mediating construct. Lee [279] tested the effect of perceived benefits on both attitude ($\beta = 0.24$, $p < 0.05$) and behavioural intention ($\beta = 0.32$, $p < 0.05$) towards internet banking, reporting a stronger effect size for the latter. Notably, a recent meta-analysis showed that perceived benefits is the most significant predictor of residential PV adoption intention [280].

However, at the latter stages of the innovation-decision process (i.e. implementation and confirmation), the focus may then shift from perceived benefits to a focus on 'benefits realised', as demonstrated by Daniel and Wilson [281] in the context of e-commerce adoption among small and medium-sized enterprises in the UK. Moreover, in the context of radio frequency identification adoption (RFID), Reyes et al. [282] showed that different stages of the innovation-decision process influence the level of perceived benefits (i.e. customer service, productivity, asset management, and communication) among supply chain professionals. A similar approach was applied by Jiménez-Martínez and Polo-Redondo [283] when examining how perceptions of benefits may change among Spanish administrations in the context of electronic data interchange. The authors made the case that benefits may be hard to perceive at first but become more tangible following adoption [283]. Consequently, increasing trialability of the technology is usually the most direct way to raise perceived benefits and adoption prospects.

As the literature has evolved, researchers have operationalised perceived benefits in several ways, reflecting both the importance and multi-faceted nature of the construct. For example, alongside perceived barriers ($\beta = 0.272$), perceived benefits ($\beta = 0.262$) had the strongest influence on willingness to participate in electronic bidding[21] in the construction industry, but also moderated the relationship between perceived barriers and participation willingness ($\beta = 0.535$) [284]. In the context of technology-enhanced

[21] i.e. the electronic issuing and receipt of any bid documentation in electronic format as part of the procurement process [284]

learning, Dubey and Sahu [285] operationalised perceived benefits as both a meditator and moderator of the relationship between adoption intention and student satisfaction, thereby applying an outcome-orientated lens.

Kim et al. [286] supported the hypotheses that the relative benefits of mobile banking positively influence consumer trust ($\beta = 0.30$, $p < 0.01$), in addition to directly predicting usage intention ($\beta = 0.18$, $p < 0.01$), with an overall effect size of 0.28. Additionally, Laforet and Li [287] observed that understanding potential benefits is critical to mobile banking adoption. However, Gong et al. [288] showed that perceived benefits mediates the relationship between trust in online health consultation services and adoption intention. Park and colleagues [289] applied a similar approach when examining the interplay between perceived risk, benefit, and trust on consumer's intention to use mobile payment services in the Midwestern United States.

Critically, it should be noted that in many contexts, perceived benefits is understood in terms of 'relative advantage' vis-à-vis Rogers' seminal classification [210].[22] For example, the study of Abou-Shouk and colleagues [290] focused on perceived benefits of e-commerce adoption among Egyptian travel agents, wherein relative advantage was characterised via three constructs composed of at least four indicators (i.e. 'essential benefits', N = 4; 'marketing and competition benefits', N = 5; and 'business internal efficiency benefit', N = 6). A more reductive approach may also prevail, as taken by Au and Enderwick [291] when defining 'perceived benefit' in terms of "the adopter's belief of the likelihood that the technology can improve the economic benefits of the organisation and/or of the person."

At the market level, sustainable consumer behaviour – which may manifest directly through low-carbon energy adoption [292] – broadly involves purchasing products which account for environmental, societal, and fair-trade concerns [293]. Consequently, sustainable consumption in the marketplace entails an environmental and socio-economic dimension. Prior research has shown that domestic hydrogen acceptance positively mediates the relationship between perceived community benefits and willingness to adopt domestic hydrogen ($\beta = 0.173$, $p < 0.001$) [108].

[22] This study engages with relative advantage by examining technology perceptions vis-à-vis boiler and hob performance.

Furthermore, it should be highlighted that the observed effect was strongest among the ten exogenous constructs included in the model [108].

In a broad sense, 'adoption potential' can be operationalised through SEM to measure the feasibility that an individual will adopt a technology according to the influence of specific factors [294]. This study leverages prior developments in the literature by developing a specific measure of adoption potential, which combines adoption willingness (ADPT1–ADPT3) and perceived community benefits (ADPT4–ADPT6) to form a comprehensive endogenous construct, consisting of six indicators. As a result, adoption potential reflects aspects of both behavioural and community acceptance.

Notably, a threefold focus on perceived community benefits is reflected in evidence submitted by Cadent Gas [259] to the UK government as part of the hydrogen heating village trial application, which specified economic, social, and environmental gains envisioned via the local trial in Whitby.[23] Crucially, perceptions related to community benefits will shape local and broader socio-political acceptance [35], in addition to influencing the potential for domestic hydrogen adoption [21,46].

Through the inclusion of indicators measuring perceived community benefits at the economic (ADPT4), social (ADPT5), and environmental level (ADPT6), the proposed construct adheres firmly to the scientific convention of employing at least three measurement items [295]. In doing so, this study overcomes prior approaches in the context of household energy adoption. For example, Sopha and Klöckner [296] measured adoption intention for wood pellet heating via two indicators,[24] while a subsequent study on biomass heating adoption employed one indicator [297].[25] Similarly, the study of Gölz and Wedderhoff [267] relied on a single indicator to measure onshore wind energy acceptance in Germany.

5.5 Conceptual framework

An overview of the hydrogen acceptance literature illustrates ways in which the field has evolved over time, as well as areas where research has seemingly stagnated or

[23] Including tackling fuel poverty, high air pollution, social isolation, and digital exclusion (social); growing the local economy, job creation, and upskilling the existing local workforce (economic); and future-proofing local consumers' homes in the transition to low-carbon heat (environmental) [259].
[24] Agreement level with the following statements: (1) When I decide next time for a new heating system, my intention to use wood pellet heating is strong; and (2) I intend to use wood pellet heating [296].
[25] i.e. Rate your degree of agreement or disagreement with the following statement: I would be willing to buy biomass heating in the near future [297].

plateaued [222,223]. One of the earliest (qualitative) models conceptualised hydrogen (fuel) acceptance to be composed of a combination of values, perceptions and wants, which are influenced by social background and personal experience [298]. Although the model in question accounted for socio-psychological dynamics, the specific dimensions of acceptance were limited mostly to risk perceptions and customer satisfaction [298], thereby presenting a somewhat narrow lens.

Gordon et al. [35] reviewed studies engaging with either fully or partially with aspects of domestic hydrogen acceptance (N = 17). Foremost, among the retrieved studies, Scott and Powells [32,66] applied a social practice theory approach [169] to examine consumer attitudes towards the domestic hydrogen transition in the North of England. Online survey results (N = 700) highlighted a clear dichotomy between perceived benefits, with 69.9% and 23.4% of respondents citing positive impacts for the environment and economy, while safety perceptions were largely neutral (68.9%) [44].

Drawing on this dataset, the mediating role of domestic hydrogen acceptance in predicting willingness to adopt domestic hydrogen appliances has been explored [108]. It was determined that perceived community benefits (β = 0.173, p < 0.001), production perceptions (β = 0.133, p < 0.001), perceived socio-economic costs (β = -0.036, p = 0.001), and safety perceptions (β = 0.037, p = 0.004) have statistically significant indirect effects on adoption intention, reflecting the presence of complementary partial mediation in the model [300,301]. While the Domestic Hydrogen Acceptance Model (DHAM) revealed critical insights on the dynamics and acceptance and adoption [108], technology perceptions and financial perceptions were not among the ten exogenous constructs tested.

Researchers including McCollum et al. [63] have demonstrated the efficacy of modelling constructs such as environmental concern, technology perceptions, and behavioural practices when examining heterogeneous preferences for low-carbon transportation, while Michelsen and Madlener [302] integrated technological, psychological, economic, and non-economic factors to examine homeowners' preferences for an innovative residential heating system. Additionally, in a seminal contribution focused on consumer decision-making for residential energy use, Wilson and Dowlatabadi [303] emphasised the importance of context, scale, and

heterogeneity in advocating for integration between social psychology, sociology, conventional economics, behavioural economics, and technology diffusion models.

Accounting for the emerging evidence base on hydrogen homes, this analysis expands on prior studies through an explicit focus on the safety, technological, economic, and environmental dimensions of adoption potential for hydrogen homes (see Fig. 5-1). The specified dimensions are of critical importance to the energy transition, as specified within the UK Hydrogen Strategy [17]. Synergies between techno-economic, technical, market, political and social dimensions [19] are required to scale up of the hydrogen economy, which will rest on several levers: realising 10GW of low-carbon hydrogen production by 2030; developing safe and reliable network infrastructure for large-scale hydrogen transport and storage; securing a competitive economic advantage within the global hydrogen market; and accelerating green growth and cross-sectoral decarbonisation [17]. In response, Fig. 5-7 internalises the call for integration while introducing a built-in multigroup focus, as reflected by the inclusion of four distinct consumer segments.

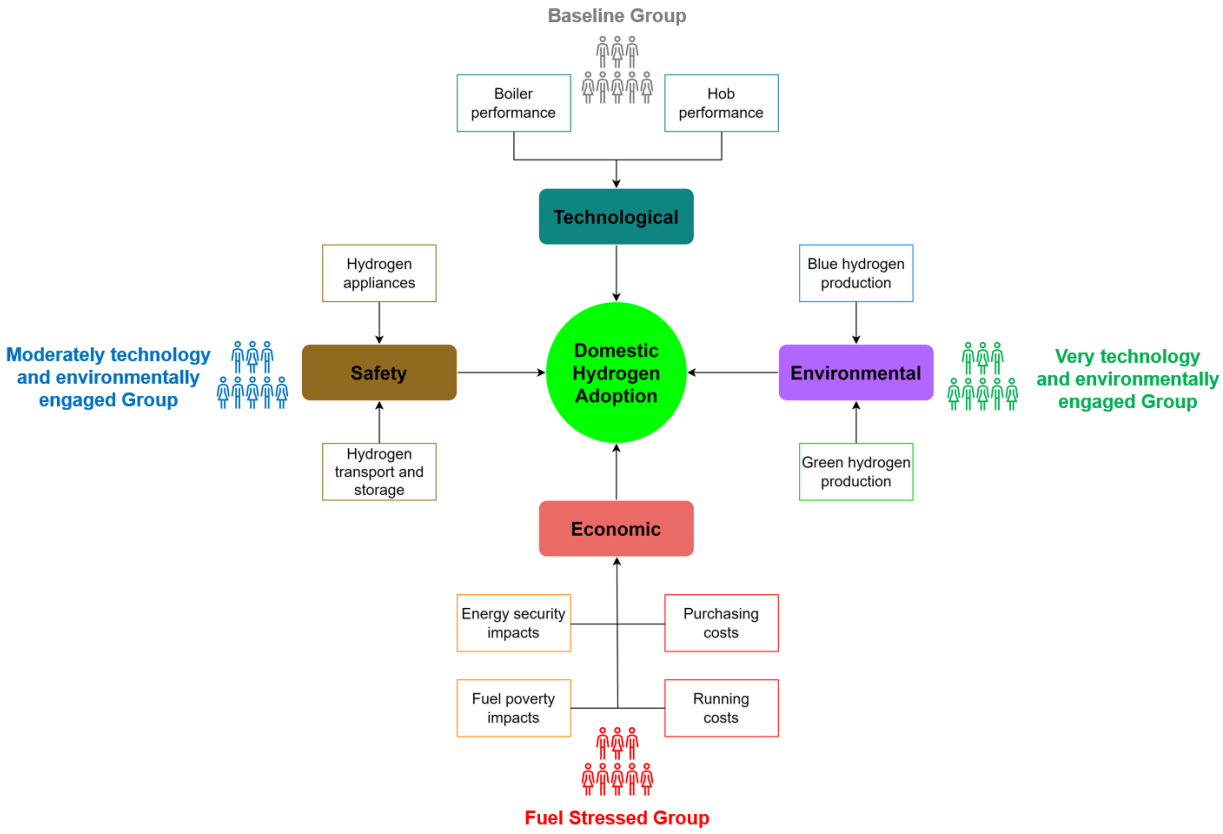


Fig. 5-7. The Safety-Technological-Economic-Environmental Perspectives (STEEP) Framework on domestic hydrogen adoption applied to multigroup analysis.

Source: Based on [304] (see Appendix K).

5.6 Results

This section reports the results of the analysis in five stages. Firstly, Section 5.6.1 relays the descriptive findings and preliminary insights from a series of K-W tests. Section 5.6.2 describes the measurement model assessment, while Section 5.6.3 outlines the three-step MICOM procedure. Next, Section 5.6.4 compares the structural models for each pairwise comparison, while Section 5.6.5 extends the MGA by conducting an IMPA to derive strategic insights for segment-specific consumer engagement.

5.6.1 Descriptive analysis and inferences from analysis of variance

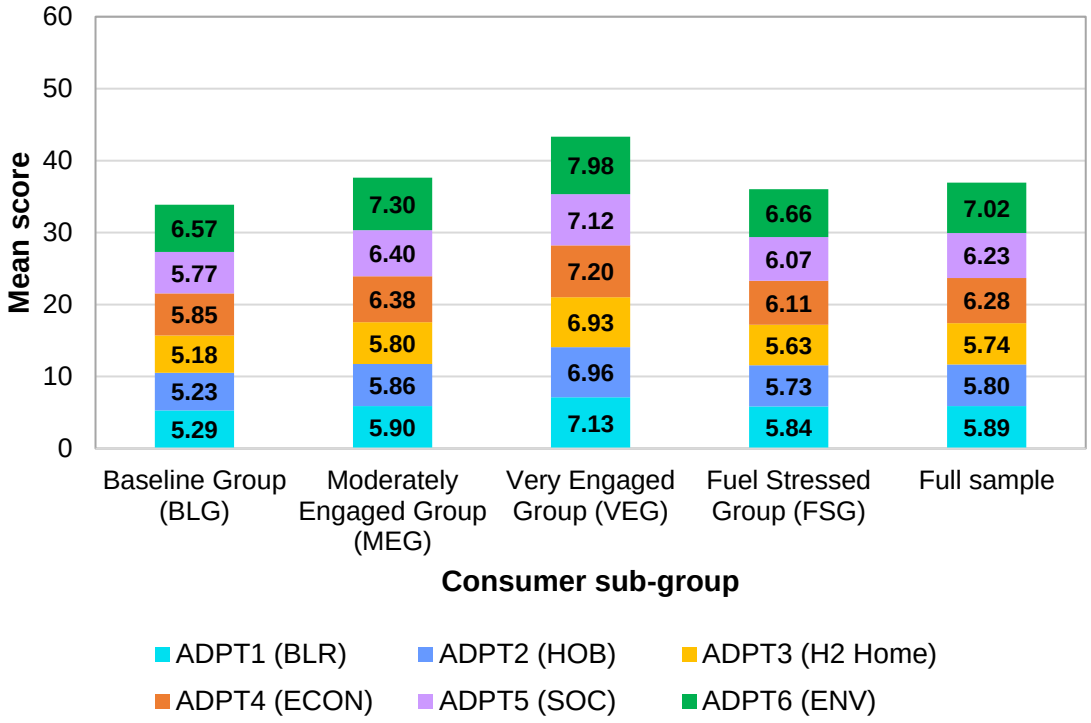
5.6.1.1 Adoption potential

Overall, from a maximum potential score of 60, the VEG showed a moderately high adoption potential (*M* = 43.3), while the BLG demonstrated the least potential (*M* = 33.9). Meanwhile, the MEG (*M* = 37.6) placed above the sample mean (*M* = 37.0), whereas the FSG fell slightly below this value (*M* = 36.0). The descriptive results suggest that technology and environmental engagement, and to a lesser extent fuel stress, are potential drivers of domestic hydrogen adoption.

Foremost, as reflected in Fig. 5-8 and Fig. 5-9, the VEG demonstrates a more positive outlook across all indicators, resulting in the following rank order: (1) VEG = 7.22; (2) MEG = 6.27; (3) FSG = 6.01; (4) BLG = 5.65. For Adoption indicators 1–3 (hydrogen boiler, hydrogen hob, hydrogen home), the following mean scores are reported: VEG = 7.01; MEG = 5.85; FSG = 5.73; BLG = 5.23. The same rank order is retained when considering the Adoption indicators 4–6, which represent perceived community benefits (economic, social, environmental): VEG, *M* = 7.43; MEG, *M* = 6.69; FSG, *M* = 6.28; BLG, *M* = 6.06.

Consequently, statistically significant differences are detected between all pairwise comparisons at the 1% level (see Table 5-6), excluding the MEG and FSG (ρ = 0.205, r = 0.07). The largest difference is observed between the VEG and BLG (r = 0.47), followed by the VEG and FSG (r = 0.38). The remaining comparisons rank as follows: MEG–VEG (*r* = 0.30); MEG–BLG (*r* = 0.20); BLG–FSG (*r* = 0.12). In view of this rank order, being very technology and environmentally engaged is the foremost driver of differences regarding adoption potential for hydrogen homes.

Further evidence highlighting the divergence between consumer sub-groups is strongly reflected in Fig. 5-9, which displays the top 10% of responses supporting and rejecting hydrogen, based on the metrics presented in Fig. 5-8 (N = 185 for outright 'accepters'; N = 185 for outright 'rejecters' (see Fig. 0-4). The results clearly demonstrate that the VEG expresses the strongest level of support for domestic hydrogen, while the BLG represents the most resistant segment. Meanwhile, the MEG is somewhat positively skewed in its attitude towards hydrogen homes in this context (i.e. considering two extreme tails of attitude), while the FSG is somewhat negatively skewed.



ADPT1 = Willingness to adopt a hydrogen boiler; ADPT2 = Willingness to adopt a hydrogen hob; ADPT3 = Willingness to adopt a hydrogen home; ADPT4 = Perceived economic benefits; ADPT5 = Perceived social benefits; ADPT6 = Perceived environmental benefits.

Fig. 5-8. Adoption potential for hydrogen homes across consumer sub-groups.

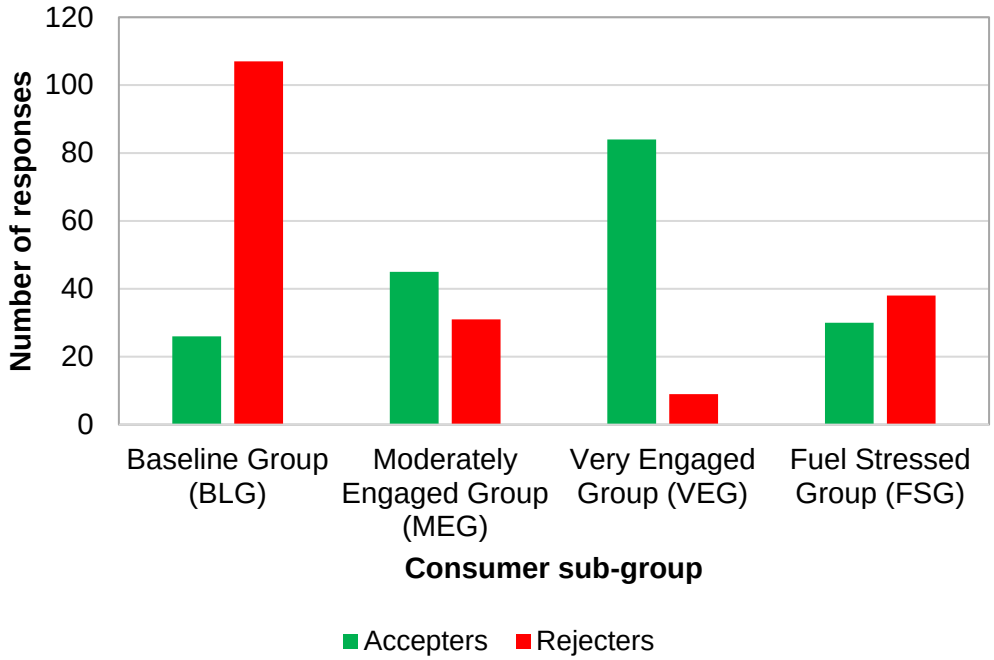


Fig. 5-9. Breakdown of hydrogen acceptance and rejection by consumer sub-group.

Table 5-6. Pairwise comparisons for domestic hydrogen adoption potential.

	BLG	MEG	VEG	FSG
BLG				
MEG	<0.001*** (0.20)			
VEG	<0.001*** (0.47)	<0.001*** (0.30)		
FSG	0.001*** (0.12)	0.205 (0.07)	<0.001*** (0.38)	

ρ-values are reported for each comparison, while the effect size given in parentheses.
*** Statistically significant at the 1% level.

5.6.1.2 Adoption constructs

Descriptive statistics show that safety, technological, economic, and environmental perspectives differ according to levels of engagement in technology and the environment. The observed patterns are highly consistent across the metrics shown in Fig. 5-10, whereby the VEG displays the most supportive response across all positive metrics – safety perceptions (SP), boiler performance (BLR), hob performance (HOB), and production perceptions (PP) – followed by the MEG. Furthermore, across each of these metrics, the FSG is marginally more supportive than the BLG. Foremost, the data suggests technology and environmental engagement is positively associated with support for the twin-track approach. Additionally, all sub-groups have an expressed preference for hydrogen heating; providing strong evidence that hydrogen boilers are the more favoured appliance. Notably, the prospect of adopting both

appliances vis-à-vis a hydrogen home fails to strengthen consumer acceptance, as illustrated in Fig. 5-8.

On the one hand, this finding is consistent with results reported by Lozano et al. [66] in the Australian context. By contrast, data from online focus groups conducted in the UK (N = 58) suggested consumers had a "prevailing tendency" to support the proposition of a hydrogen home over individual technology pathways [46]. The discrepancy likely reflects differences in the characteristics of quantitative and qualitative research methods [305–307]. Conceivably, online survey respondents take a more objective comparative assessment when evaluating the three metrics. By contrast, focus group respondents may transmit higher levels of subjectivity based on interactions with others [308,309], and learning through conversation and information provision [310,311], which seemingly boosted positivity towards hydrogen homes [46].

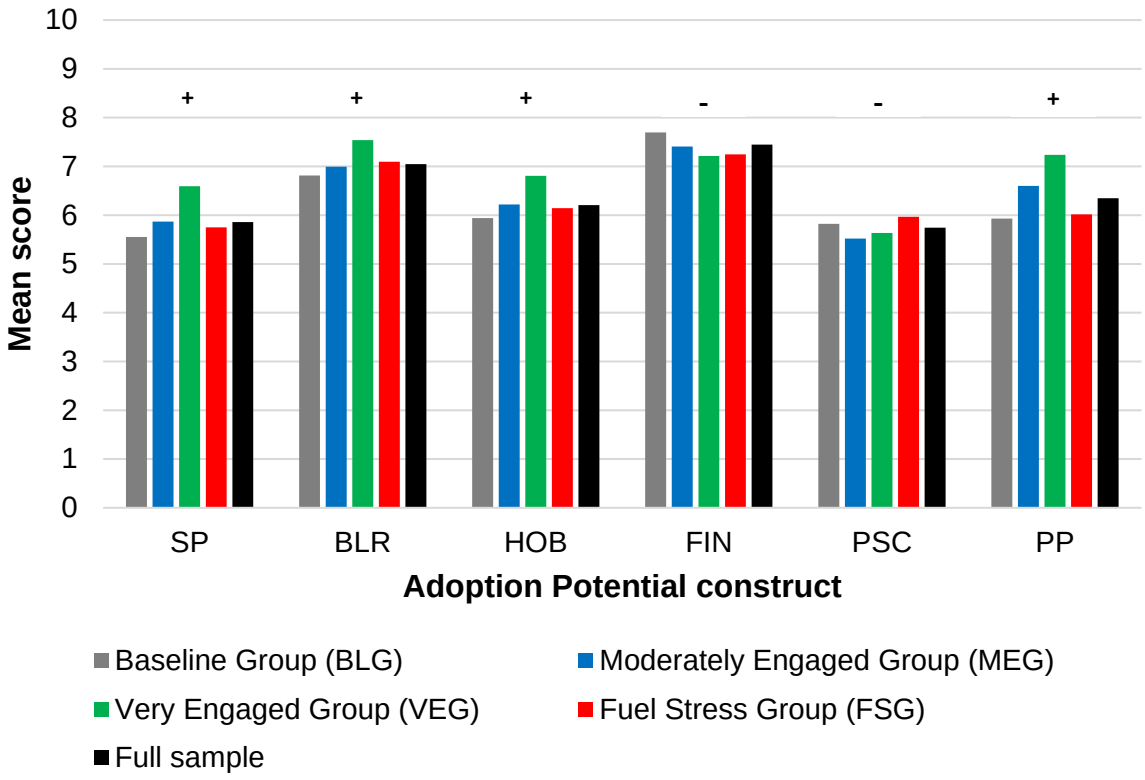


Fig. 5-10. Descriptive results for adoption constructs across consumer sub-groups.

SP = Safety Perceptions; BLR = Boiler Performance; HOB = Hob Performance; FIN = Financial Perceptions; PSC = Perceived Socio-economic Costs; PP = Production Perceptions.

Positive constructs are denoted by a plus sign (+)
Negative constructs are denoted by a minus sign (-)

In terms of negative constructs – financial perceptions (FP) and perceived socio-economic costs (PSC) – the previous sequencing (i.e. VEG, MEG, FSG, BLG) diverges in both cases. For FP, the BLG holds the most negative position, followed by the MEG, FSG, and VEG. However, for PSC, the FSG has the highest level of concern, followed by the BLG, VEG, and MEG (see Fig. 5-10). Although the evidence suggests that technology and environmental engagement is associated with lower economic concerns, this trend could be due to socio-demographic factors such as annual income, which is partially inferred by the FSG having the strongest macro-economic concerns in relation to fuel poverty and energy insecurity.

Based on the preliminary descriptive and statistical analyses, Production Perceptions corresponds to the construct with the most variance across the sub-groups ($SD = 0.60$, $t = 207.36$, $p < 0.001$), followed by Safety Perceptions ($SD = 0.45$, $t = 85.97$, $p < 0.001$). Thereafter, the sub-constructs of Technological Perceptions present mid-level variance: Boiler Performance: $SD = 0.31$, $t = 31.570$, $p < 0.001$; Hob Performance: $SD = 0.37$, $t = 49.12$, $p < 0.001$). Finally, constructs composing the economic dimension present comparatively less variance: Financial Perceptions: $SD = 0.22$, $t = 29.93$, $p < 0.001$; Perceived Socio-economic costs: $SD = 0.20$. $t = 10.54$, $p = 0.014$.

Ahead of conducting PLS-MGA, it is suggested that the environmental dimension of domestic hydrogen adoption potential has the highest level of heterogeneity, followed by the safety, technological, and economic dimensions (see Table 5-7 and Appendix 0). To overcome the limitations of the K-W test (see Section 5.2.2) and establish more robust comparative insights, PLS-MGA is carried out, as reported in Sections 5.6.2–5.6.5. Crucially, PLS-MGA supports both parametric and non-parametric tests (see Section 5.6.3). Critically, whereas the K-W test is performed via univariate analysis [111] – relying on post-hoc calculations to calculate *p*-values and effect sizes – PLS-MGA provides a more robust (second-generation) multivariate technique [312,313].

Table 5-7. Kruskal-Wallis H Test results for adoption factors.

		Safety Perceptions		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	<0.021****** (0.09)			
VEG	<0.001******* (0.29)	<0.001******* (0.22)		
FSG	0.556 (0.05)	1.000 (0.03)	<0.001******* (0.25)	
		Boiler Performance		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.344 (0.06)			
VEG	<0.001******* (0.18)	0.002******* (0.13)		
FSG	0.081 (0.08)	1.000 (0.02)	0.025****** (0.11)	
		Hob Performance		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.044 (0.08)			
VEG	<0.001******* (0.22)	<0.001******* (0.15)		
FSG	0.713 (0.05)	1.000 (0.03)	0.001******* (0.18)	
		Financial Perceptions		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	<0.001******* (0.10)			
VEG	<0.001******* (0.14)	0.985 (0.05)		
FSG	<0.001******* (0.13)	1.000 (0.04)	1.000 (0.01)	
		Perceived Socio-economic Costs		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	0.320 (0.06)			
VEG	0.095***** (0.08)	1.000 (0.02)		
FSG	1.000 (0.02)	0.179 (0.08)	0.056***** (0.10)	
		Production Perceptions		
	BLG	**MEG**	**VEG**	**FSG**
BLG				
MEG	<0.001******* (0.23)			
VEG	<0.001******* (0.41)	<0.001******* (0.21)		
FSG	1.000 (0.02)	<0.001******* (0.21)	<0.001******* (0.42)	

ρ-values are reported for each comparison, while the effect size given in parentheses.
******* Statistically significant at the 1% level.
****** Statistically significant at the 5% level.
***** Statistically significant at the 10% level.

5.6.2 Measurement model assessment

Item reliability is supported when indicator loadings exceed a Cronbach Alpha (CA) value of 0.708 [93,99], signifying that that the construct explains more than 50% of the

variance in an associated indicator [93]. The proposed model is composed of 29 indicators, resulting in total of 116 measurements across all sub-groups. Overall, only 8.6% (N = 10) of indicators measured below 0.708 (see Appendix 0), but crucially all values were above 0.4 which is acceptable when conducting exploratory research and testing new measurement items [94,314]. As a result, indicators such as PP1 were retained to support content validity [314], which is a common occurrence when carrying out social science research and establishing new theoretical model [314]. This decision was supported since other reliability and validity requirements were fulfilled, as described in the following sub-sections.

5.6.2.1 Internal consistency reliability

Internal consistency reliability tests the extent to which indicator variables load on their assigned construct (i.e. latent variable) [315]. The recommended threshold for Composite Reliability (CR) is a value above 0.70 [94], although 0.60 may be permitted when conducting exploratory research [68]. As reported in Table 5-8, rho_a (ρ_A)[26] [315], all values except for Safety Perceptions ($\rho_A = 0.916$) measured between 0.70 and 0.90 for the BLG, thereby satisfying recommended guidelines. All ρ_A values fell between 0.70 and 0.90 for the FSG, whereas two values exceeded 0.90 for the MEG (SP = 0.925; FP = 0.933), while the safety perceptions construct measured 0.931 for the VEG. Critically, all results fell below less stringent upper threshold of 0.95, thereby supporting content validity and suggesting minimal risk of indicator redundancy [93].

5.6.2.2 Convergent and discriminant validity

The last stage of assessing the measurement model involves establishing convergent validity and discriminant validity [316,317]. To support convergent validity, the recommended average variance extracted (AVE)[27] for each construct should exceed 0.50, which indicates that, on average, the construct explains more than 50% of the variance of its items [317]. As reported in Table 5-8, this condition was met in all cases for the BLG and also fulfilled for all remaining sub-groups (see Table 0-6–Table 0-14).

[26] Formally, the Henseler and Dijkstra rho [315]. ρ_A is the most robust measure of internal consistency, usually reporting a value between CA and Dillon-Goldstein rho_c (ρ_C), which estimate lower and upper bounds [93].
[27] Calculated as the mean of the squared loadings for all indicators associated with a construct [317].

Table 5-8. Baseline Group: Assessment of reliability, convergent validity, and multicollinearity.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety Perceptions (SP)	0.911	0.916	0.934	0.738	1.356
Boiler Attributes (BLR)*	0.703	0.712	0.818	0.532	1.602
Hob Attributes (HOB)*	0.839	0.841	0.893	0.675	1.602
Technology Perceptions (TP)**	0.760	0.760	0.893	0.807[a]	1.254
Financial Perceptions (FP)	0.759	0.767	0.802	0.581	1.119
Perceived Socio-economic Costs (PSC)	0.703	0.724	0.869	0.769[b]	1.208
Production Perceptions (PP)	0.841	0.872	0.885	0.610	1.167
Adoption Potential (ADPT)	0.841	0.854	0.876	0.541	n/a

** Higher-order construct
* Lower order constructs
[a] Results for validating the higher order construct (TP) are reported in Fig. 0-5.
[b] Since PSC has two indicators, the AVE is by default larger than 0.50

Discriminant validity establishes whether constructs can be considered empirically distinct from one another [93], whereby indicator loadings should be highest in relation to the target construct [68,94], as tested via the Fornell Larcker criterion [318] and fulfilled for each sub-group (see Table 5-9). Henseler and colleagues [316] developed the heterotrait-monotrait (HTMT) ratio of correlations as a more sensitive and robust measure of discriminant validity [319,320]. Discriminant validity was further supported since each construct fell below the more stringent threshold of 0.85 [316], as documented in Table 5-10. Additionally, no instances of multicollinearity were observed since all VIF scores measured below the threshold of 3.0 [99].

Table 5-9. Baseline Group: Fornell Larcker results for assessing of discriminant validity.

	BLR	FP	HOB	ADPT	PC	PP	SP
BLR	0.729						
FP	-0.107	0.763					
HOB	0.613	-0.130	0.822				
ADPT	0.494	-0.262	0.486	0.735			
PSC	-0.140	0.310	-0.135	-0.350	0.877		
PP	0.208	-0.087	0.212	0.458	-0.279	0.781	
SP	0.337	-0.139	0.423	0.491	-0.214	0.283	0.859

Table 5-10. Baseline Group: Heterotrait-monotrait results for assessing discriminant validity.

	BLR	FP	HOB	ADPT	PSC	PP	SP
BLR							
FP	0.167						
HOB	0.797	0.112					
ADPT	0.599	0.254	0.520				
PSC	0.203	0.286	0.175	0.417			
PP	0.251	0.106	0.244	0.478	0.350		
SP	0.425	0.119	0.484	0.528	0.267	0.321	

5.6.3 Measurement invariance test of composite models

Following the measurement model assessment, the MICOM procedure was employed to validate the scope of comparing sub-groups via PLS-MGA [62,68,69]. Firstly, configural invariance was established by ensuring identical treatment when configuring the STEEP model for each sub-group [62]. Additionally, compositional was verified by ensuring that the composite scores across all sub-groups are perfectly correlated [115]. At the final stage, partial measurement invariance was established for five of the six group comparisons (see Table 5-11), thereby confirming the validity of evaluating group-specific differences [62,115]. In one case, full measurement invariance was established (between the MEG and FSG), which infers the groups can be considered homogenous and the datasets can be pooled.

Having established the grounds for conducting MGA in PLS-SEM [62,115], the intended objective could be fulfilled by analysing the potential differences in path coefficients for each pairwise comparison. Accordingly, PLS-MGA tests the null hypothesis that the population parameters (i.e. structural path coefficients) are equal across two sub-groups ($H_0 : \theta^{(1)} = \theta^{(2)}$) [113].

Results from PLS-MGA indicate different degrees of consumer heterogeneity between five of the six pairwise comparisons, with the MEG and FSG testing non-significant (i.e. homogenous) following composite equality, as previously acknowledged and reported for completeness in Table 5-11 and Fig. 5-12. In the following summary, results for the permutation ρ-value are reported (see Table 5-12) as this metric is considered the most robust of the available tests [113].

Firstly, when comparing the **BLG** and **MEG**, two statistically significant differences are observed, namely, for technology perceptions (permutation ρ-value = 0.014) and

perceived socio-economic costs (permutation ρ-value = 0.012). Additionally, the result for safety perceptions proved significant at the 10% level (permutation ρ-value = 0.087).

Secondly, two constructs have distinct effects on domestic hydrogen adoption potential when considering the **BLG** and **VEG**. Foremost, technology perceptions is statistically significant at the 1% level (permutation ρ-value = 0.008), while production perceptions is significant at the 5% level (permutation ρ-value = 0.027). Additionally, safety perceptions is close to significant at the 10% level (permutation ρ-value = 0.103), which is in line with the previous observation between the BLG and MEG. Overall, the data suggests that respondents with higher levels technology and environmental engagement present different hydrogen perceptions when compared against a control group.

Thirdly, a statistically significant finding is recorded between the **BLG** and **FSG** in relation to technology perceptions (permutation ρ-value = 0.021). Furthermore, perceived socio-economic costs (permutation ρ-value = 0.010) and production preferences (permutation ρ-value = 0.022) present statistically significant differences between the **MEG** and **VEG**. Finally, production preferences are significantly different between the **VEG** and **FSG**, albeit at the 10% level (permutation ρ-value = 0.083).

Based on these observations, it can be inferred that four constructs – technology perceptions, perceived socio-economic costs, safety perceptions, and production preferences – partially explain differences between consumer sub-groups in relation to domestic hydrogen adoption potential. By contrast, perceptions of financial factors appear to be somewhat homogenous across the sub-samples, while the performance aspects of hydrogen boilers and hobs is perceived similarly across consumer segments. The next stage builds upon these findings by comparing the path coefficients between structural models for each sub-group and discussing the implications of the results.

5.6.4 Structural model assessment

The bootstrapping procedure (5000 sub-samples) [109] was applied to statistically examine the proposed hypotheses (see Section 5.3) for each consumer sub-group (see Fig. 0-6**Fig. 0-*6***–Fig. 0-9). As reported in Table 5-13, the model explains domestic hydrogen adoption potential meaningfully in all cases, albeit with some notable

intricacies between sub-groups (see Fig. 5-11). Supporting the reliability of the proposed model (see Section 5.6.4.2), in-sample predictive power for each sub-group proved comparable to the full sample (R^2 = 0.535): BLG = 0.502; MEG = 0.539; VEG = 0.538; and FSG = 0.478.

For the BLG, all results proved significant at the 0.1% level. For the MEG, six tests returned a ρ-value of <0.001, while the result for financial perceptions was near equivalent (ρ = 0.001). In the case of the VEG, similar patterns were detected since most results proved significant at the less than 0.1%, while technology perceptions was near equivalent (ρ = 0.001). However, one construct, namely, financial perceptions, proved close to significant at the 5% level (ρ = 0.052). Consequently, this relationship presents an outlier within the MGA. Lastly, for the FSG, technology perceptions (ρ = 0.002) and financial perceptions (ρ = 0.006) proved statistically significant at the 1% level, while all other constructs returned a ρ-value of <0.001.

As a result, hypotheses **H1a** (SP), **H2a** (BLR), **H2b** (HOB), **H2c** (TP), **H4a** (PSC), and **H5a** (PP) are supported for each consumer sub-group. Regarding the influence of financial perceptions (FP) on domestic hydrogen adoption potential, the stated hypothesis (**H3a**) is fully supported for the BLG, MEG, and FSG, but only partially supported for the VEG. However, H3a is rejected for the VEG in view of comparative findings reported in Table 5-12,, which categorised this result as a clear outlier in the study, since statistical significance could not be established at the 5% level.

Table 5-11. Assessment of equal distribution of mean values and variances of composites.

	Equal Mean Value				Equal Variances				
Group comparison	**Original difference**	**Permutation mean difference**	**95% confidence interval**	**Permutation *p*-value**	**Original difference**	**Permutation mean difference**	**95% confidence interval**	**Permutation *p*-value**	**Full measurement variance established**
BLG-MEG									
SP	-0.184	0.000	[-0.121;0.118]	0.001	-0.079	0.004	[-0.154-0.161]	0.342	No
BLR	-0.097	-0.001	[-0.120;0.114]	**0.116**	-0.043	0.003	[-0.208-0.220]	**0.678**	**Yes**
FP	0.145	0.000	[-0.116;0.115]	0.014	0.175	0.003	[-0.155-0.170]	0.036	No
HOB	-0.140	0.001	[-0.122;0.116]	0.022	-0.057	0.002	[-0.201-0.204]	0.560	No
PSC	0.181	0.001	[-0.118;0.115]	0.002	-0.057	0.000	[-0.166-0.169]	0.521	No
PP	-0.484	0.002	[-0.120;0.124]	0.000	0.214	-0.002	[-0.178-0.158]	0.017	No
TP	-0.134	0.000	[-0.120;0.115]	0.027	-0.058	0.002	[-0.214-0.217]	0.598	No
BLG-VEG									
SP	-0.576	-0.001	[-0.132;0.127]	0.000	-0.186	0.005	[-0.178-0.175]	0.034	No
BLR	-0.394	0.003	[-0.123;0.136]	0.000	0.013	0.000	[-0.220-0.220]	0.896	No
FP	0.255	-0.003	[-0.136;0.119]	0.000	0.116	0.006	[-0.192-0.224]	0.258	No
HOB	-0.431	0.002	[-0.125;0.132]	0.000	-0.074	-0.001	[-0.204-0.218]	0.511	No
PSC	0.103	0.002	[-0.131;0.128]	0.127	-0.557	0.004	[-0.169-0.182]	0.000	No
PP	-0.868	-0.002	[-0.132;0.130]	0.000	0.194	0.004	[-0.176-0.174]	0.037	No
TP	0.456	0.002	[-0.123;0.138]	0.000	-0.071	-0.001	[-0.214-0.237]	0.564	No
BLG-FSG									
SP	-0.118	0.002	[-0.124;0.126]	**0.067**	0.050	0.001	[-0.179-0.186]	**0.577**	**Yes**
BLR	-0.154	0.000	[-0.134;0.124]	0.013	0.015	0.000	[-0.210-0.200]	0.886	No
FP	0.216	0.002	[-0.127;0.129]	0.002	0.080	0.000	[-0.159-0.159]	0.350	No
HOB	-0.107	-0.001	[-0.129;0.133]	**0.096**	0.045	0.002	[-0.200-0.212]	**0.685**	**Yes**
PSC	-0.084	0.001	[-0.131;0.126]	**0.197**	-0.137	-0.001	[-0.171-0.168]	**0.119**	**Yes**
PP	-0.059	0.001	[-0.119;0.129]	**0.382**	0.109	0.003	[-0.173-0.198]	**0.235**	**Yes**
TP	-0.141	-0.001	[-0.124;0.123]	0.028	0.045	0.002	[-0.209-0.222]	0.664	No
MEG-VEG									
SP	-0.396	-0.002	[-0.138-0.132]	0.000	-0.109	0.002	[-0.186-0.197]	0.257	No
BLR	-0.293	-0.001	[-0.147;0.135]	0.000	0.056	0.002	[-0.260-0.273]	0.656	No
FP	0.087	-0.001	[-0.141;0.142]	**0.239**	-0.046	0.002	[-0.196-0.204]	**0.670**	**Yes**
HOB	-0.291	-0.003	[-0.146;0.132]	0.000	-0.016	0.004	[-0.223-0.237]	0.897	No
PSC	-0.060	-0.001	[-0.137;0.139]	0.401	-0.504	0.004	[-0.178-0.178]	0.000	No
PP	-0.482	-0.003	[-0.142-0.132]	0.000	0.003	0.004	[-0.174-0.180]	0.978	No

TP	-0.319	-0.003	[-0.138-0.137]	0.000	-0.010	0.004	[-0.252-0.259]	0.934	No
MEG-FSG									
SP	0.069	-0.003	[-0.133;0.133]	**0.294**	0.129	0.003	[-0.217-0.210]	**0.221**	**Yes**
BLR	-0.057	-0.001	[-0.135;0.136]	**0.424**	0.056	0.000	[-0.255-0.235]	**0.662**	**Yes**
FP	0.091	-0.005	[-0.148;0.133]	**0.202**	-0.101	0.001	[-0.180-0.169]	**0.265**	**Yes**
HOB	0.036	0.000	[-0.153;0.137]	**0.601**	0.102	0.003	[-0.200-0.223]	**0.353**	**Yes**
PSC	-0.258	0.000	[-0.141;0.140]	**0.001**	-0.079	0.006	[-0.169-0.196]	**0.397**	**Yes**
PP	0.448	0.000	[-0.138;0.129]	**0.000**	-0.106	0.003	[-0.185-0.195]	**0.294**	**Yes**
TP	-0.003	-0.001	[-0.146;0.141]	**0.962**	0.102	0.002	[-0.228-0.239]	**0.388**	**Yes**
VEG-FSG									
SP	0.470	0.003	[-0.143;0.154]	0.000	0.237	0.002	[-0.226-0.206]	0.030	No
BLR	0.245	0.000	[-0.146;0.158]	0.002	-0.004	0.002	[-0.236-0.240]	0.968	No
FP	0.027	0.000	[-0.147;0.153]	**0.727**	-0.055	0.002	[-0.219-0.215]	**0.634**	**Yes**
HOB	0.334	0.001	[-0.141;0.151]	0.000	0.121	0.002	[-0.248-0.219]	0.300	No
PSC	-0.171	0.003	[-0.148;0.145]	0.028	0.431	-0.003	[-0.179-0.168]	0.000	No
PP	0.849	0.001	[-0.151;0.145]	0.000	-0.089	0.002	[-0.192-0.203]	0.413	No
TP	0.327	0.001	[-0.147;0.148]	0.000	0.117	0.003	[-0.260-0.245]	0.349	No

Table 5-12. Comparative assessment of path coefficients within the structural model for each pairwise comparison.

Group comparison	Path coefficients		Statistical test				
BLG–MEG	**BLG**	**MEG**	**Absolute difference**	**Parametric t-test (equal var.)**	**Parametric t-test (unequal var.)**	**MGA two-tailed**	**Permutation *ρ*-value**
SP → ADPT	0.220	0.316	-0.096	0.075	0.073	0.075	0.087*****
BLR → TP	0.477	0.493	-0.016	0.437	0.441	0.439	0.416
HOB → TP	0.633	0.613	0.021	0.394	0.387	0.384	0.351
TP → ADPT	0.352	0.217	0.136	0.020	0.019	0.018	0.014******
FP → ADPT	-0.118	-0.123	0.004	0.923	0.923	0.916	0.911
PSC → ADPT	-0.138	-0.269	0.131	0.009	0.010	0.010	0.012******
PP → ADPT	0.265	0.251	0.014	0.779	0.778	0.779	0.798
BLG–VEG	**BLG**	**VEG**	**Absolute difference**	**Parametric t-test (equal var.)**	**Parametric t-test (unequal var.)**	**MGA two-tailed**	**Permutation *ρ*-value**
SP → ADPT	0.220	0.320	-0.099	0.102	0.106	0.105	0.103
BLR → TP	0.477	0.461	0.017	0.425	0.382	0.379	0.403
HOB → TP	0.633	0.629	0.004	0.865	0.855	0.851	0.880
TP → ADPT	0.352	0.181	0.171	0.010	0.009	0.010	0.008*******
FP → ADPT	-0.118	-0.074	-0.045	0.366	0.350	0.350	0.340
PSC → ADPT	-0.138	-0.141	0.003	0.957	0.953	0.957	0.952
PP → ADPT	0.265	0.377	-0.113	0.047	0.048	0.052	0.027******
BLG–FSG	**BLG**	**FSG**	**Absolute difference**	**Parametric t-test (equal var.)**	**Parametric t-test (unequal var.)**	**MGA two-tailed**	**Permutation *ρ*-value**
SP → ADPT	0.220	0.284	-0.064	0.286	0.301	0.302	0.280
BLR → TP	0.477	0.461	0.017	0.468	0.487	0.485	0.465
HOB → TP	0.633	0.656	-0.022	0.416	0.427	0.425	0.429
TP → ADPT	0.352	0.200	0.113	0.029	0.039	0.040	0.021******
FP → ADPT	-0.118	-0.131	0.152	0.808	0.818	0.799	0.789
PSC → ADPT	-0.138	-0.193	0.054	0.293	0.289	0.290	0.277
PP → ADPT	0.265	0.265	0.000	0.995	0.995	0.999	0.995
MEG – VEG	**MEG**	**VEG**	**Absolute difference**	**Parametric t-test (equal var.)**	**Parametric t-test (unequal var.)**	**MGA two-tailed**	**Permutation *ρ*-value**

SP → ADPT	0.316	0.320	-0.004	0.956	0.956	0.960	0.944
BLR → TP	0.493	0.461	0.033	0.149	0.130	0.126	0.137
HOB → TP	0.613	0.629	-0.016	0.534	0.526	0.523	0.536
TP → ADPT	0.217	0.181	0.035	0.602	0.605	0.604	0.579
FP → ADPT	-0.123	-0.074	-0.049	0.349	0.348	0.341	0.341
PSC → ADPT	-0.269	-0.141	-0.128	0.021	0.015	0.015	0.010**
PP → ADPT	0.251	0.377	-0.127	0.037	0.038	0.040	0.022**
MEG–FSG	**MEG**	**FSG**	**Absolute difference**	**Parametric t-test (equal var.)**	**Parametric t-test (unequal var.)**	**MGA two-tailed**	**Permutation *ρ*-value**
SP → ADPT	0.316	0.284	0.032	0.624	0.628	0.627	0.603
BLR → TP	0.493	0.461	0.033	0.203	0.207	0.204	0.198
HOB → TP	0.613	0.656	-0.043	0.135	0.141	0.138	0.146
TP → ADPT	0.217	0.200	0.016	0.825	0.829	0.827	0.831
FP → ADPT	-0.123	-0.131	0.008	0.887	0.889	0.877	0.890
PSC → ADPT	-0.269	-0.193	-0.076	0.182	0.179	0.177	0.169
PP → ADPT	0.251	0.265	-0.014	0.815	0.816	0.814	0.805
VEG–FSG	**VEG**	**FSG**	**Absolute difference**	**Parametric t-test (equal var.)**	**Parametric t-test (unequal var.)**	**MGA two-tailed**	**Permutation *ρ*-value**
SP → ADPT	0.320	0.284	0.035	0.626	0.625	0.627	0.606
BLR → TP	0.461	0.461	0.000	0.996	0.996	0.996	0.998
HOB → TP	0.629	0.656	-0.027	0.374	0.365	0.363	0.374
TP → ADPT	0.181	0.200	-0.019	0.820	0.818	0.819	0.831
FP → ADPT	-0.074	-0.131	0.057	0.352	0.343	0.336	0.332
PSC → ADPT	-0.141	-0.193	0.051	0.340	0.333	0.333	0.287
PP → ADPT	0.377	0.265	0.113	0.084	0.084	0.086	0.083*

*** Statistically significant at the 1% level.
** Statistically significant at the 5% level.
* Statistically significant at the 10% level.

Table 5-13. Results of path analysis and hypothesis testing for consumer sub-groups.

Baseline Group					
Hypothesis	***β* coefficient**	***t*-statistic**	***ρ*-value**	***f*²**	**Result**
H1a: SP → (+/-) ADPT	0.220	6.387	<0.001	0.075*	Accepted
H2a: BLR → (+) TP	0.477	37.036	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.633	39.841	<0.001	n/a	Accepted
H2c: TP → (+) ADPT	0.352	9.196	<0.001	0.199**	Accepted
H3a: FP → (-) ADPT	-0.118	4.055	<0.001	0.025*	Accepted
H4a: PSC → (-) ADPT	-0.138	4.431	<0.001	0.032*	Accepted
H5a: PP → (+/-) ADPT	0.265	8.200	<0.001	0.121*	Accepted
Moderately Engaged Group					
Hypothesis	***β* coefficient**	***t*-statistic**	***ρ*-value**	***f*²**	**Result**
H1a: SP → (+/-) ADPT	0.316	7.769	<0.001	0.177**	Accepted
H2a: BLR → (+) TP	0.493	30.042	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.613	34.459	<0.001	n/a	Accepted
H2c: TP → (+) ADPT	0.217	5.037	<0.001	0.088*	Accepted
H3a: FP → (-) ADPT	-0.123	3.379	0.001	0.031*	Accepted
H4a: PSC → (-) ADPT	-0.269	6.750	<0.001	0.131*	Accepted
H5a: PP → (+/-) ADPT	0.251	6.447	<0.001	0.109*	Accepted
Very Engaged Group					
Hypothesis	***β* coefficient**	***t*-statistic**	***ρ*-value**	***f*²**	**Result**
H1a: SP → (+/-) ADPT	0.320	6.303	<0.001	0.141*	Accepted
H2a: BLR → (+) TP	0.461	32.897	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.629	34.268	<0.001	n/a	Accepted
H2c: TP → (+) ADPT	0.181	3.391	0.001	0.050*	Accepted
H3a: FP → (-) ADPT	-0.074	1.944	0.052	0.011	Rejected
H4a: PSC → (-) ADPT	-0.141	4.107	<0.001	0.041*	Accepted
H5a: PP → (+/-) ADPT	0.377	8.048	<0.001	0.246**	Accepted
Fuel Stressed Group					
Hypothesis	***β* coefficient**	***t*-statistic**	***ρ*-value**	***f*²**	**Result**
H1a: SP → (+/-) ADPT	0.284	5.538	<0.001	0.120*	Accepted
H2a: BLR → (+) TP	0.461	23.115	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.656	28.469	<0.001	n/a	Accepted
H2c: TP → (+) ADPT	0.200	3.176	0.002	0.058*	Accepted
H3a: FP → (-) ADPT	-0.131	2.772	0.006	0.030*	Accepted
H4a: PSC → (-) ADPT	-0.193	4.755	<0.001	0.058*	Accepted
H5a: PP → (+/-) ADPT	0.265	5.825	<0.001	0.114*	Accepted

** Moderate effect size
* Small effect

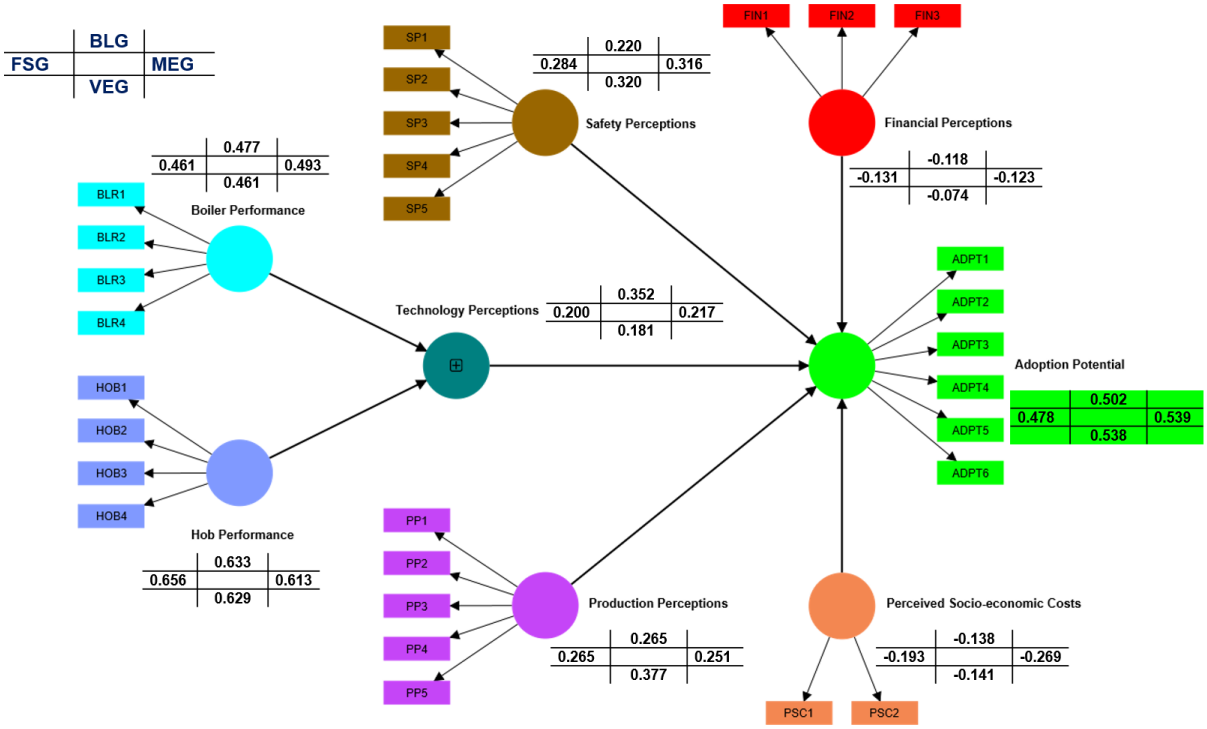


Fig. 5-11. Structural model path coefficients for consumer sub-groups.

BLG = Baseline Group; MEG = Moderately technology and environmentally Engaged Group; VEG = Very technology and environmentally Engaged Group; FSG = Fuel Stressed Group.

5.6.4.1 Multigroup analysis of structural models

The results reported in Table 5-13 enable in-depth comparative analysis regarding the observed differences between sub-groups. Firstly, in terms of safety perceptions (**H1a**), the effect size is moderate for the MEG (f^2 = 0.177), but small across the remaining sub-groups (f^2 = 0.075–0.141). Foremost, the positive effect of hydrogen safety is notably smaller for the BLG (β = 0.220) compared to other sub-groups (β = 0.284–0.320). As a result, **H1b** is partially supported in view of group-specific differences between the BLG and MEG, which are significant at the 10% level (ρ = 0.087).

Secondly, in terms of technology perceptions (**H2c**), a notable difference is detected between the BLG and other consumer sub-groups. Although the path coefficients for boiler performance (**H2a:** β = 0.461–0.493) and hob performance (**H2b:** β = 0.613–0.656) are relatively consistent across all groups, leading to comparable outcomes for each hypothesis (ρ = <0.001), this range widens when testing **H2c**: β = 0.181–0.352. A moderate effect size is reported for the **BLG** (f^2 = 0.199), whereas all other groups present a small effect for the TP construct (f^2 = 0.050–0.088). Although **H2d** and **H2e** are rejected due to conformity regarding perceptions of individual appliances, **H2f** is

fully supported in view of statistically significant differences between the BLG and MEG, and BLG and FSG at the 1% level, in addition to stronger divergence between the BLG and VEG (ρ = 0.008).

In respect to financial perceptions (**H3a**), small effect sizes are reported for all groups (f^2 = 0.025–0.031), except the VEG which is non-significant (β = 0.074; f^2 = 0.011). Consequently, at the individual sub-group level, H3a is rejected for the **VEG**, which is the only hypothesis unsupported across the MGA. While results from the MICOM procedure suggest homogeneity between sub-groups regarding financial perceptions, the subsequent assessment highlights a discrepancy which infers a degree of consumer heterogeneity. While **H3b** is rejected due to a lack of group-specific differences, the evaluation of respective path coefficients presents the VEG as an outlier in respect to the FP construct. As discussed in Section 5.7, this divergence may be attributed to the influence of socio-demographic variables such as income level and involvement in financial decision-making. For example, in the Chinese context, Lei et al. [51] showed that high-income consumers are more likely to have a pro-environmental preference and early adoption potential, whereas lower income groups follow a more rational purchasing preference for energy-efficient home appliances.

Regarding perceived socio-economic costs (**H4a**), while the effect size is small for all sub-groups, the influence of this construct is notably stronger among the MEG (β = 0.269, f^2 = 0.131), whereas other sub-groups are comparatively more homogenous (β = 0.138–0.193; f^2 = 0.032–0.058). **H4b** is fully supported following group-specific differences between both the BLG and MEG, and BLG and VEG, which proved significant around the 1% level.

Lastly, the positive influence of production perceptions (**H5a**) on domestic hydrogen adoption potential is highest among the VEG (β = 0.377), corresponding to a moderate effect (f^2 = 0.246). By contrast, this relationship is highly consistent across the remaining sub-groups (β = 0.251–0.265), yielding a weak to moderate positive effect on domestic hydrogen adoption potential (f^2 = 0.109–0.121).

In summary, the PLS-MGA highlights group-specific differences in relation to all constructs within the model, excluding the lower order constructs which leads to rejection of **H2d** (Boiler Performance) and **H2e** (Hob Performance). The following patterns emerge from the data in regard to adoption potential for hydrogen homes: the

positive effect of technology perceptions is highest for the BLG; the negative effect of financial perceptions is least pronounced and non-significant at the 5% level for the VEG; the negative effect of perceived socio-economic costs is highest for the MEG; the positive effect of safety perceptions registers strongest for the MEG and least for the BLG; and finally, the positive effect of production perceptions is markedly higher for the VEG (see Fig. 0-8).

5.6.4.2 In-sample and out-of-sample predictive power

Following the comparative assessment of structural models, in-sample (i.e. explanatory) and out-of-sample predictive power [321–323] are evaluated for each sub-group (see Table 5-14 and Table 0-15). Firstly, the coefficient of determination (R^2) reports the level of variance explained by all predictor variables in relation to the final endogenous construct [83,323,324], namely domestic hydrogen adoption potential. A general rule of thumb suggests R^2 values of 0.25, 0.50, and 0.75 reflect small, medium, and large effect sizes [325]. However, as documented in social science studies, R^2 is influenced by the nature of the subject matter, with large effect sizes seldom reported [326,327].

In-sample predictive power closely converged across the sub-groups, ranging from R^2 = 0.478 for the FSG, to R^2 = 0.539 for the MEG (Mean R^2 = 0.514; R^2 for the full sample = 0.535). Consequently, the STEEP model demonstrates moderate in-sample predictive power, explaining around 50% of the variance in adoption potential across consumer sub-groups.

An initial measure of out-of-sample predictive power by calculating the Stone-Geisser's Q^2 value for the endogenous construct [328,329]. Q^2 results approximated or exceeded 0.50, indicating moderate to strong predictive power for each sub-group [93]: BLG = 0.490; MEG = 0.520; VEG = 0.516; FSG = 0.451. To further assess out-of-sample predictive power [330], this analysis draws on the $PLS_{predict}$ tool developed by Shmueli et al. [331] and the cross-validated predictive ability test (CVPAT) espoused by Liengaard et al. [332].

For the BLG, four out of the six adoption indicators outperformed the naïve linear model (LM) [93]. For the MEG and VEG, this held true for three indicators, while all six indicators outperformed the LM benchmark for the FSG. Accordingly, results from $PLS_{predict}$ suggest that STEEP framework has high out-of-sample predictive power when tested on the FSG, while other sub-samples exhibit moderate predictive power [93]. Additionally, out-of-sample predictive power proved higher for each sub-group as compared to the full sample (Table 0-15).

Table 5-14. Results of predictive power using $PLS_{predict}$.

Items	Q^2predict	Root mean square error (RMSE)[a]		Mean absolute error (MAE)[b]	
		PLS-SEM	Linear model	PL-SEM	Linear model
Baseline Group					
ADPT1	0.099	0.888	0.889	0.711	0.712
ADPT2	0.093	0.910	0.913	0.724	0.731
ADPT3	0.111	0.892	0.890	0.708	0.707
ADPT4	0.333	1.599	1.641	1.229	1.249
ADPT5	0.385	1.649	1.650	1.274	1.269
ADPT6	0.401	1.663	1.553	1.292	1.183
Moderately Engaged Group					
ADPT1	0.098	0.913	0.915	0.732	0.726
ADPT2	0.108	0.927	0.932	0.750	0.747
ADPT3	0.128	0.941	0.949	0.758	0.755
ADPT4	0.342	1.557	1.550	1.170	1.183
ADPT5	0.421	1.532	1.517	1.189	1.194
ADPT6	0.386	1.503	1.482	1.193	1.147
Very Engaged Group					
ADPT1	0.173	0.882	0.889	0.698	0.707
ADPT2	0.178	0.923	0.949	0.737	0.767
ADPT3	0.171	0.953	0.946	0.766	0.773
ADPT4	0.331	1.633	1.656	1.199	1.276
ADPT5	0.416	1.607	1.579	1.187	1.201
ADPT6	0.280	1.462	1.395	1.160	1.114
Fuel Stressed Group					
ADPT1	0.099	0.911	0.920	0.727	0.729
ADPT2	0.155	0.866	0.873	0.688	0.685
ADPT3	0.165	0.931	0.953	0.750	0.747
ADPT4	0.295	1.688	1.763	1.313	1.352
ADPT5	0.299	1.771	1.818	1.373	1.383
ADPT6	0.362	1.665	1.686	1.305	1.267

[a] The square root of the average of the squared differences between the predictions and the actual observations.
[b] The square root of the average of the squared differences between the predictions and the actual observations.

Results from the CVPAT corroborate this finding, since the average difference between the PLS-SEM model and the indicator average (IA) proved negative, and significantly below zero [332]. However, as reported in Table 5-15, the model lacks strong predictive accuracy for the BLG, MEG, and VEG, since it fails to outperform the more conservative linear model (LM) prediction benchmark [333]. Nevertheless, results for the FSG reinforce the relatively strong predictive capabilities of the STEEP framework for examining the antecedents of domestic hydrogen adoption potential (t = 2.402, ρ = 0.017).

Table 5-15. CVPAT benchmark and results for predictive ability test.

		PLS-SEM vs. Indicator average (IA)			
Adoption Potential	**PLS loss**	**IA loss**	**Average loss difference**	**t value**	***p* value**
BLG	1.743	2.594	-0.852	10.344	<0.001
MEG	1.601	2.386	-0.785	9.234	<0.001
VEG	1.654	2.408	-0.754	6.973	<0.001
FSG	1.876	2.617	-0.750	7.819	<0.001
		PLS-SEM vs. Linear Model (LM)			
Adoption Potential	**PLS loss**	**IA loss**	**Average loss difference**	**t value**	***p* value**
BLG	1.743	1.708	0.035	1.475	0.141
MEG	1.601	1.585	0.016	0.519	0.604
VEG	1.654	1.628	0.026	0.501	0.617
FSG	1.867	1.962	-0.095	2.402	0.017

5.6.5 Importance-performance map analysis for sub-models

To extract additional value from the PLS-MGA, an IMPA is conducted for each sub-group to identify priority zones for strengthening domestic hydrogen adoption potential (see Table 0-16, and Fig. 0-10–Fig. 0-13). The output from the IMPA helps visualise the differences between sub-groups (see Fig. 5-12), which can help guide policy makers and key stakeholders when taking strategic decisions on hydrogen homes.

5.6.5.1 Baseline Group

For respondents in the BLG, which foreseeably represents the larger proportion of UK society, technology perceptions is the most influential predictor of adoption potential, followed by production and safety perceptions. It follows that more strategic efforts are needed to assure consumers that hydrogen home appliances have a performance advantage over existing natural gas boilers and hobs. Between hydrogen heating and cooking, evidence suggests that cooking contributes more strongly towards technology perceptions.

In terms of negative predictors, financial perceptions and perceived socio-economic costs have a similar effect on adoption potential. However, more resources should be allocated to mitigating socio-economic concerns, since this construct had the lowest latent variable (LV) index value (i.e. worst performance) in the model (LV = 48.056). By contrast, constructs located at the positive end of the importance-performance matrix are clustered closely together.

5.6.5.2 Moderately Engaged Group

Following the trend observed with the BLG, positive constructs are also clustered tightly for the MEG in terms of appliance performance, albeit with a marginal increase overall. Safety perceptions ranks as the most critical predictor of domestic hydrogen adoption potential, followed by perceived socio-economic costs. Moreover, these constructs have the lowest performance (SP: LV = 58.745; PSC: LV = 44.189), which reinforces the need for strategic measures to address the safety and macro-economic dimensions of domestic hydrogen adoption.

Production perceptions is the next most important positive predictor, followed by technology perceptions, with little discrepancy in terms of their respective performance. However, hydrogen cooking (hob performance) has a lower LV score (HOB = 62.318) compared to its heating counterpart (BLR = 70.113). This observation should be factored into decision-making around domestic hydrogen trials by consolidating the justification for converting hob appliances. Lastly, in comparative terms, financial perceptions appear to be less relevant to the MEG compared to other adoption constructs, which calls for further interrogation and validation in follow-up studies, for example, by testing for moderating effects related to socio-demographic variables.

5.6.5.3 Very Engaged Group

Respondents with high levels of technology and environmental engagement attribute most importance to production perceptions (β = 0.377), whereas technology perceptions has more a moderate influence (β = 0.181). However, no discernible difference was detected between these constructs in terms of performance (PP: LV = 73.558; TP: LV = 71.659). Safety perceptions (β = 0.320; LV = 66.027) is the next most critical factor to address after production perceptions, whereas perceived socio-

economic costs (β = -0.141) has a slighter smaller total effect than technology perceptions, but a considerably lower performance (LV = 45.081).

Mirroring results for the MEG, financial perceptions is the least influential factor. Interestingly, boiler performance has the highest LV index value among constructs (BLR = 75.718), which implies consumer perceptions of hydrogen heating are well captured by the four measurement instruments within the survey. Conversely, additional survey questions are needed to better reflect hob performance. For example, specific items related to perceptions of performance and controllability for different types of cooking (e.g. boiling and simmering, grilling, wok stir-frying etc.).

5.6.5.4 Fuel Stressed Group

In comparison to other sub-groups, fuel stressed respondents present a narrow range within the IMPA, since no positive construct exceeds 0.300, while negative constructs are below -0.200 on the x-axis. This clustering effect corresponds to near equal levels of importance being attributed to the safety and production aspects of the domestic hydrogen transition, which represent the foremost areas of strategic importance. As a result, fuel stressed respondents transmit less overall divergence in perceptions of different adoption factors, which demarcates this sub-group as more homogenous within the overall context of the STEEP framework.

Technology perceptions (β = 0.200; LV = 65.634) and perceived socio-economic costs (β = -0.193; LV = 49.664) have near equivalent effect sizes. However, there is more scope for improving adoption potential by allocating resources towards mitigating socio-economic concerns, which aligns to the disproportionate livelihood pressures facing fuel stressed citizens [169]. Despite this imperative, when evaluated against other adoption factors, the FSG nevertheless place least weight on the micro-economic dimension associated with the purchasing and running costs of hydrogen appliances.

Finally, the previously observed pattern regarding hydrogen cooking remains consistent, confirming the need to improve perceptions of hob performance. Based on the results, it can be conjectured that citizens facing fuel stress pressures perceive hydrogen home appliances as a potential mechanism for alleviating safety concerns and improving the environment, which is consistent with prior research [31,46].

Fig. 5-12. Importance-performance map analysis of domestic hydrogen adoption potential for consumer sub-groups. Turquoise = Boiler Performance (BLR); Blue = Hob Performance (HOB); Green = Technology Perceptions (TP); Red = Financial Perceptions (FP); Orange = Perceived Socio-economic Costs (PSC); Brown = Safety Perceptions (SP); Purple = Production Perceptions (PP).

5.7 Discussion

Firstly, it must be emphasised that the MEG and FSG present highly consistent results, reflecting the finding of full measurement invariance reported via the MICOM procedure (see Table 5-11), which yields relatively similar importance-performance maps. Nevertheless, visualising these results within the presented quadrant format is highly instructive for analytical purposes. In all other cases, elements of consumer heterogeneity are detected and observable (see Fig. 5-12). This section further discusses these dynamics and explores potential sources of consumer heterogeneity associated with the influence of socio-structural and socio-demographic factors.[77]

The analysis suggests that the foremost near-term priority for increasing adoption potential across the general population lies with strengthening technology perceptions of domestic hydrogen, since this construct held the most influence across the BLG. Additionally, production perceptions and to a lesser degree, safety perceptions, must be factored into policy making and strategic decisions to promote positive perceptions of hydrogen homes for the wider UK population. However, as technology and environmental engagement levels increase and reach a high level, production perceptions and safety perceptions become focal points for strengthening adoption potential, while the technological dimension related to hydrogen appliances is less pronounced. The observed pattern also holds partially true when technology and environmental engagement levels are moderate and under conditions of fuel stress. Safety perceptions appear marginally more important than production perceptions for both the MEG and FSG, while technology perceptions remains the least relevant positive construct.

Regarding negative effects related to micro- and macro-economic factors, the IMPA suggests that financial perceptions are comparatively less important than other factors during the pre-deployment stage of the transition. This relationship may reflect the specificity of acceptance dynamics when appliances are still being tested and yet to be commercialised. Furthermore, the online survey framed the adoption decision for ‘before 2030’, which may have indirectly reduced attention attributed towards potential financial risks. Critically, research on rooftop solar PV adoption in Texas has emphasised how financial perceptions (i.e. perceived affordability) becomes a more significant factor as consumers progress through the decision-making process [334], which may entail five distinct stages: Knowledge → Persuasion → Decision →

Implementation → Confirmation [210]. Studies on a range of energy technology use cases support the notion that consumers attribute greater importance to financial factors when the adoption decision is imminent, as opposed to hypothetical [35,219,335].

It follows that during the formative stage of the transition, seeking to strengthen public perceptions of financial costs may be somewhat premature and fail to translate into a shift towards optimism and positivity on the 'hydrogen acceptance matrix', which includes pessimism, scepticism, and cautiousness at the negative end [78]. However, should the safety and environmental case for domestic hydrogen be established, financial costs may likely emerge as the foremost factor in predicting adoption potential and market acceptance [36]. Nevertheless, the announced 'price promise' made by the boiler industry's leading manufacturers (Worcester Bosch, Vaillant, Baxi, and Ideal) must be fulfilled to pre-empt grounds for significant consumer backlash [336], while a corresponding 'price pledge' on energy bills would be welcomed strongly by UK households given the current climate of ongoing economic instability [75].

Overall, the findings suggest that non-economic constructs such as safety and technology perceptions [21,44] are potentially more influential during the formative phase of technology diffusion. As argued by Bull [337], market choices often involve a trade-off between several heterogeneous factors such as functionality, performance, and price, with consumers being more likely to concentrate on salient characteristics (i.e. efficiency performance) as opposed to unpredictable factors such as future energy costs.

Currently, *social acceptance* is mainly at stake for hydrogen homes [36] ahead of consumer decision-making and prospective adoption [35,219,334,335], should a scaling up be greenlighted by the government in the upcoming years [17]. It emerges that prospects for implementing hydrogen village trials in places such as Redcar, Yorkshire [338,339] and Fife, East-central Scotland [28] may hinge firmly on communicating the potential for economic, social, and environmental benefits at the community level [108,259,263]. The evidence suggests that consolidating *community acceptance* is a prerequisite to enabling *household acceptance*, which would correspond to the subsequent adoption of hydrogen homes appliances (i.e. *market acceptance*) following local trials.

In terms of consumer heterogeneity, the findings on financial perceptions may be partially attributed to variation in certain socio-demographic variables between sub-groups (see Table 0-2), which could potentially moderate the relationship between examined constructs and adoption potential for domestic hydrogen. Moderation occurs when the effect on an exogenous construct on an endogenous construct is not constant but depends on the values of a third construct (i.e. the moderating variable) [340–342]. Such relationships should be thoroughly examined to advance theoretical knowledge [111,340].

Notably, the VEG had the largest representation of outright property owners compared to the sample average (+10.2%), whereas mortgage owners were under-represented compared to other the sub-groups. This composition may have translated to a more financially secure group with comparatively lower economic concerns at the household level. Support for this notion is directly observed when examining distributions for annual income brackets. The VEG had the lowest representation of respondents with an income below £23,500 (-9.7%), alongside over-representation for the highest income bracket of £62,500+ (+11.2%). Such discrepancies are likely to have mitigated concerns related to financial concerns and may have influenced other adoption constructs such as perceived socio-economic costs.

Regarding perceived socio-economic costs, negativity or concern was attributed foremost to the MEG, which appears somewhat counterintuitive. One possible source of divergence may originate from the interaction between location and area type, which corresponded to an over-representation of respondents from rural parts of Wales and the Southwest of England for the MEG. Policy studies show that this demographic group are highly susceptible to fuel poverty risks [343,344]; especially among Welsh households where around 17% of rural households are classified as fuel poor compared to 13% for urban areas [345]. Furthermore, the MEG had a lower representation of urban respondents compared to the sample average (-3.9%), whereas the VEG was over-represented (+6.8%).

Additionally, it should be noted that the VEG was over-represented by respondents from the Southeast and London (+8.1%), whereas over-representation within the FSG corresponded to respondents from the North of England and Scotland (+7.9%). However, in the case of the FSG, to an extent, the higher representation was

intentionally targeted to make the group more nationally representative of UK fuel poverty patterns. This divergence feeds into potential group-specific differences which may be linked to location and reflective of the North-South divide [57,346].

While housing tenure, location, and area type appear to be relevant socio-structural variables, age and gender may also prove important socio-demographic variables, alongside income. Notably, in terms of age, respondents within the VEG were both the youngest (-3.8%) and the oldest (+5.7%). By contrast, the FSG was significantly under-represented by respondents aged 55 and over (-7.4%). It is feasible that an increase in age contributes towards a more negative financial perception, as older households may contend with more liabilities and feel risk averse to technology change. Notably, Lozano et al. [66] found that older individuals were more unlikely to support domestic hydrogen in the Australian context.

Interestingly, an early study on hydrogen acceptance conducted in the Netherlands shows that older age groups had the strongest perception of hydrogen as unsafe [183], however, subsequent studies are yet to validate this finding. It is also plausible that the partially significant difference between the MEG and BLG for safety perceptions (p = 0.075) stems from under-representation of older respondents within the FSG. Future studies can explore whether differences in age are likely to amplify or weaken the positive effect of safety perceptions on domestic hydrogen adoption potential.

While age may moderate several relationships within the model, gender differences could also help explain some of the observed patterns. Foremost, there was a substantial over-representation of female respondents within the BLG (+7.1%). Other less pronounced differences also defined the distribution of the MEG and VEG, while the FSG was close to nationally representative in terms of gender. Foremost, gender may have significantly influenced consumer heterogeneity when comparing the dynamics of technology perceptions, as suggested in previous studies on various energy technologies [347,348] including hydrogen [66,349].

Notably, *environmental benefits* proved the most the significant predictor of consumer heterogeneity when examining qualitative response patterns to this survey [34]. Despite other areas of mixed alignment between results, the PLS-MGA fully validates the notion that perceived environmental benefits (a proxy of production perceptions or environmental attitude) is the most heterogeneous factor of domestic hydrogen

acceptance. As a result, findings form this dataset deviate from previous exploratory research, which suggested the twin-track strategy, in its totality, would be most strongly supported by fuel stressed respondents [31].

At a finer level, the small-sample study (N = 58) identified technology and renewable energy engaged respondents to be supportive, whereas environmentally engaged citizens were critical of blue hydrogen and had least support for the twin-track approach [31]. However, findings from this large sample survey (N = 1845) indicate that the combination of technology and environmental engagement enhances the positive effect of production perceptions on domestic hydrogen adoption potential. The implication is that environmental concerns associated with a blue hydrogen production pathway are potentially insufficient to override wider support for the energy transition, and by proxy, the deployment of low-carbon hydrogen heating and cooking appliances.

Statistical support for this argument has been provided by Gordon et al. [34] in finding the effect of environmental engagement on domestic hydrogen adoption potential (β = 0.287) to be weaker than the effect of knowledge and awareness of renewable energy technologies (β = 0.308), and moreover, consumer innovativeness (i.e. interest in being an early adopter of new energy technologies: β = 0.324). A closer inspection of the filtering results reported in Fig. 5-2 lends potential support for the observed patterns. For all sub-groups, except the MEG, consumer innovativeness levels were higher compared to interest and engagement level in environmental issues, as well knowledge and awareness of renewable energy technologies.

As reported in Table 5-16, the difference was most pronounced in the case of the VEG and FSG, but also notably higher for the BLG, whereas consumer innovativeness ranked second for the MEG. It is also noteworthy that the FSG presented a higher overall score than the BLG, wherein minimal divergence was observed regarding environmental engagement levels (difference = 0.04). The larger discrepancy between technology engagement levels for the FSG and BLG may further explain underlying patterns of consumer heterogeneity observed within the data, alongside the non-significant result between the MEG and FSG. Future research should engage with these dynamics by demarcating between a very technology and a very environmentally engaged group to validate these observations.

Table 5-16. Breakdown of results for categorical filtering results across consumer sub-groups

	Consumer sub-group			
Categorical filter	**BLG**	**MEG**	**VEG**	**FSG**
Interest and engagement level in environmental issues	2.46	3.52	4.16	2.50
Knowledge and awareness of renewable energy technologies	2.14	3.22	4.19	2.42
Consumer innovativeness	2.61	3.43	4.59	2.94
Total	7.20	10.18	12.94	7.86

In summary, it may be reasoned that controlling for a range of variables such as age, gender, income, and location may influence the dynamics of consumer heterogeneity observed within this study, whereby some relationships may be amplified, while others are weakened. For example, being older may increase financial concerns, while higher annual income may reduce socio-economic concerns. In response, subsequent studies should conduct moderation analysis and simple slope analysis in PLS-SEM [111,350,351] to examine the potential (moderating) effects of a range of categorical and continuous variables [111]. Critically, testing for moderating effects must have a firm theoretical basis and follow specific guidelines [111], which can be established and applied in follow-up research to distil additional insights on consumer heterogeneity in the context of domestic hydrogen adoption potential.

5.8 Conclusion

Drawing on modelling techniques such as PLS-MGA [49], business researchers have increasingly factored heterogeneity into their studies on consumer acceptance [324,352], as reflected by the dominance of multigroup analyses in management journals [62]. However, as reviewed in Section 5.3, energy acceptance scholars [51] have been relatively slow to adopt multigroup analyses (see Fig. 5-4). Furthermore, to date, most multigroup studies tend to constrain their focus to just two groups; even in instances where comparing more groups makes theoretical and empirical sense [62]. Such tendencies stifle research progress towards uncovering critical insights on consumer heterogeneity. Given potential implications for future energy pathways [353,354] and emissions reduction [355], reversing this trend is especially important in the context of emerging low-carbon technologies [356] such as domestic hydrogen [35,357].

This study makes a substantial contribution to the emerging literature on hydrogen acceptance [222,223] and wider field of energy transitions [358,359] by presenting a novel multigroup approach, which is applied to the context of hydrogen homes in the UK. For the first time, analytical insights are derived by differentiating between three levels of technology and environmental engagement – very engaged, moderately engaged, and non-engaged – while explicitly accounting for fuel stress in the segmentation approach (see Table 2-1).

While previous studies have taken a mostly binary approach by comparing the effects of innovation category [66], or gender and political party preferences [67], on hydrogen acceptance, this study is the first to present a multi-dimensional focus on consumer perceptions and preferences, while shifting the focus towards hydrogen adoption potential. This lens is critical for advancing insights on the parameters of market acceptance [46,75], alongside other acceptance dimensions [36], which is a necessary step for bolstering the growth potential of the hydrogen economy [47].

The results of this analysis resonate with the call from Lei at al. [51] for “common but differentiated household mitigation policies” to support the implementation of energy-saving policies in the urban China. In the case of hydrogen homes, results from the inter-group comparison support the need for segment-specific engagement strategies to strengthen adoption potential across the population. Identifying and aiming to better understand differences between consumer segments should become a focal point of energy research, ahead of policy decisions on the technology portfolio for residential decarbonisation [16,17]. Through a deeper comprehension of the emerging contours of consumer heterogeneity [34], policy makers and key stakeholders can respond by fine tuning their engagement strategies to increase social acceptance at different stages of the domestic hydrogen transition.

Synthesising the results from the PLS-MGA (see Fig. 5-11) and IMPA (Fig. 5-12), this study highlights several critical insights which should be validated in subsequent studies. When considering the impact of different levels of technology and environmental engagement, the data suggests that higher levels of engagement correspond to a stronger influence of production perceptions on adoption potential, thereby elevating the importance of the environmental dimension.

After production perceptions, safety perceptions is the next most influential construct among respondents composing the VEG, however, these dynamics are reversed among respondents in the MEG. Bridging the gap between the VEG and MEG, the effect size of production perceptions and safety perceptions is near equal among respondents who are non-engaged and fuel stressed. However, technology perceptions emerges as the most influential construct for respondents who are non-engaged and non-fuel stressed within the BLG.

This striking divergence underlines the scope for increasing domestic hydrogen acceptance and associated adoption potential by communicating the performance advantages of appliances (i.e. boilers and hobs) to the wider population, while targeting information on environmental and safety benefits to other consumer segments. These measures should be prioritised during the formative phase of the transition to establish the requisite level of consumer acceptance to trial and potentially deploy hydrogen homes at scale. Furthermore, future studies should further investigate the dynamics of technology perceptions in view of appliance performance, which may be achieved by introducing additional measurement items.

Finally, going forward it is highly probable that financial perceptions will become a more influential adoption factor, whereas concerns associated with energy insecurity and fuel poverty feature more prominently at this stage of the transition. However, it should be noted that this relationship is less evident for the BLG, which may be attributed to lower levels of awareness in respect to energy and environmental justice, compared to other segments.

Future research can overcome certain limitations within this study (see Section 5.7) by securing a more nationally representative sample at the sub-group level, which would allow for thorough examination of moderation effects. Subsequent multigroup approaches should aim to demarcate between technology and environmental engagement by filtering these categories within the research design. Adopting this approach will open new research avenues for comparing fuel stressed respondents who are engaged and non-engaged with technology and the environment. Conducting such a comparison may help reveal more nuanced findings regarding priority areas for enhancing hydrogen acceptance. At the same time, this study motivates the need to sample fuel poor respondents, as opposed to citizens experience high levels of fuel

stress, as a means of validating the findings and seeking a stricter energy justice lens within the research design [169,360].

Other research angles can be explored in future studies such as comparing consumers from the devolved nations of the UK [57], or applying a sub-national multigroup approach to explore regional acceptance dynamics [267]. Advancing insights at the national level is an important stepping-stone towards conducting cross-national comparative analyses. Furthermore, researchers should seek to extend the evidence base on the hydrogen economy by evaluating consumer attitudes towards different hydrogen energy technologies and alternative production pathways [67,268,276]. Additionally, it is critical to examine public perceptions of different residential decarbonisation pathways at the national level, as recently highlighted by Becker et al. [18] and Thomas and colleagues [220]. A starting point is to expand the early contribution of Williams et al. [219] through a more systematic analysis of domestic hydrogen and heat pumps.

As net-zero policy making continues to evolve in countries such as the UK, energy researchers can support decision-making processes by exploring novel ways to model the adoption potential of emerging technologies such as domestic hydrogen. A more fine-grained level of analysis can be achieved by extending the scope of MGA to support the notion of common but differentiated consumer engagement strategies. Through a hybrid focus on segments of the UK population, this study lays the groundwork for advancing the use of PLS-MGA [49,115], as a key mechanism for guiding policy making and managerial decisions on social aspects of the hydrogen economy.

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6 GENERAL DISCUSSION

With the UK government seeking to accelerate the phase out of natural gas appliances across the housing sector [1], this PhD thesis was motivated by the pressing need to ensure social acceptance is embedded into residential decarbonisation policy. Specifically, the government anticipates that a policy decision on the role of hydrogen homes should be taken in 2026, following the release of the UK Hydrogen Strategy in August 2021 [2]. However, to minimise the risk of a socially rejected transition to domestic hydrogen – underscored by the recent collapse of proposed village trials for hydrogen homes [3,4] – policy making should be supported by robust research efforts "to understand consumer acceptability and behaviour" [5]. In response, this thesis set out to develop a comprehensive understanding of the dynamics of domestic hydrogen acceptance and adoption during the formative stage of the (prospective) transition to hydrogen homes.

Comprehending these dynamics was supported through four research components: developing a multi-dimensional conceptual framework in Chapter 2; advancing an empirically-grounded typology of domestic hydrogen acceptance in Chapter 3; validating a structural equation model for domestic hydrogen acceptance in Chapter 4; and finally, validating a structural equation model for domestic adoption potential and applying multigroup analysis in Chapter 5. While Chapter 3 provided initial insights into the 'emerging contours of consumer heterogeneity' [6], Chapters 4 and 5 enriched the evidence base on the critical factors underlying consumer support for hydrogen home appliances.

The remainder of this chapter discusses the significance of the research within the context of the literature and elaborates on the practical implications of the findings to policy makers and key stakeholders; namely, the industrial sponsor, Cadent Gas, and other gas distribution network operators (GDNOs) pursuing hydrogen village trials in the UK. The discussion is supported by synthesising the results from the empirical chapters to provide actionable measures for increasing the social acceptance and adoption potential of hydrogen homes across the UK population. Firstly, Section 6.1.1 outlines general guidelines for supporting domestic hydrogen acceptance, leading to more specific recommendations in Section 6.1.2, which includes a focus on technology perceptions, productions perceptions, and segment-specific strategies.

6.1 Practical and policy implications

6.1.1 General recommendations for supporting domestic hydrogen acceptance

This thesis demonstrates that strategic measures are needed to strengthen specific psychological and attitudinal parameters across the UK population, if strides are to be taken towards strengthening domestic hydrogen acceptance. In view of the evidence base, it is anticipated that scaling up renewable energy deployment, including community-led projects [7–9], would yield positive 'spillover effects' for hydrogen acceptance [10]. Scholars such as Khalil and Dincer [11] affirm the need to focus on the role of social acceptance in shaping national- and community-level energy transitions in support of sustainable development, which aligns to the pressing need to address fuel poverty in the UK context [12,13], while supporting the growth of renewable energy communities [14,15].

A more direct synergy for encouraging the adoption of hydrogen home appliances may also lie with deepening consumer engagement in smart home technologies [16,17], alongside raising awareness of technology innovation to help increase consumer innovativeness [18]. Relatedly, enabling conditions for net-zero will rest with increasing climate change engagement between generations [19], thereby raising the environmental awareness across society to support the national hydrogen economy [20] and decarbonisation pathways for the residential sector [1,2].

Results from PLS-SEM suggest that knowledge and awareness are less influential acceptance factors than emotional drivers during the formative stage of the transition (see Fig. 4-4). At the same time, a pronounced knowledge deficit regarding domestic hydrogen, and hydrogen in general, has been shown to influence consumer attitudes, in addition to explaining perceptual divergence between sub-groups of the population (see Fig. 3-6 and Fig. 3-12). In response, specific action plans are needed to increase awareness and knowledge for renewable energy across the general population, as a stimulus for bolstering hydrogen experience, engagement, and acceptance [20–22]. This is especially critical in view of the finding that cognitive factors become more significant as consumers advance through the innovation-decision process, as shown in Fig. 4-7 and Table 4-10.

Information provision has been highlighted as a critical acceptance factor for consumers in the UK [23,24], Europe [25], Asia [21,26], and Australia [27,28]. Notably, research conducted in Australia [28,29] has flagged the importance of disseminating information on the potential costs, benefits, and risks of HETs. In response, UK stakeholders should focus on communicating the prospective socio-economic and environmental benefits of low-carbon hydrogen [30–32], while taking necessary steps to address perceived and actual risk factors [33].

Information campaigns for domestic hydrogen [34] present a low-hanging, sensitive intervention point for shifting the underlying dynamics [35] and public debate around hydrogen [36] in support of decarbonisation efforts [37]. As van Voss and Rafaty [38] argue in the more challenging context of coal phase-out in China, “relatively minor but well-targeted interventions can generate major behavioural changes and nonlinear shifts towards achieving climate mitigation goals.”

Further strategic interventions can be targeted towards increasing the observability and trialability [39,40] of hydrogen home appliances. Observability refers to how visible and perceptible the perceived benefits of domestic hydrogen are to the public, while trialability denotes the extent to which hydrogen home appliances may be experimented with and experienced by consumers prior to adoption [41]. To date, opportunities for experimentation have been restricted to limited project sites, such as the Hydrogen Experience Centre in Ellesmere Port, Northwest England [42], which was designed to inform residents about prospective plans for a hydrogen village trial in the area [43,44]. However, following government-led analysis of consumer attitudes regarding hypothetical hydrogen trials (via 4 focus groups; N = 39) [23], policy plans for village trials have failed to secure community acceptance, amid public backlash over misinformation and injustice [45,46].

Community resistance to local energy projects is well-documented in the energy transitions literature [47–49], reflecting the need for local consent and consumer engagement in areas shortlisted for hydrogen homes. Wider efforts to increase observability and trialability across different UK industrial clusters [50] and other locations around the country [51,52] would help legitimise the hydrogen industry’s social license to operate [53,54], and likely offset some degree of consumer scepticism and mistrust in energy companies and GDNOs.

The role of intermediary actors such as industry associations [55] and non-government organisations [56], as well as middle actors such as building professionals [57,58] and project managers [59], will further shape the dynamics of trust and acceptance for hydrogen transition [60,61]. Foremost, boiler manufacturers such as the 'Big Four' (Worcester Bosch, Vaillant, Baxi and Ideal) alongside the industry's trade association, the Energy and Utilities Alliance (EUA), are tasked with mitigating consumer concerns regarding the performance and safety of hydrogen appliances, while delivering on their promise to make hydrogen boilers price-competitive [62,63].

In the Welsh context, Thomas et al. [64] flagged the importance of mitigating financial risks to counteract grounds for consumer resistance to hydrogen homes, which emerged as a primary sub-factor in this analysis (see Fig. 3-6). Alongside the current 'price promise' on boiler appliances, a corresponding 'price pledge' on energy bills would help garner support for hydrogen homes in the face of socio-economic pressures [13]. As reported via multigroup analysis, fuel stress – when controlling for other variables – may influence support for hydrogen homes in a positive direction. Amid the growing fuel poverty crisis [65], it follows that a significant proportion of the population will be staking their support for domestic hydrogen on its prospective financial impacts.

The main responsibility for converting fears over domestic hydrogen into hopes [66] lies with the government and energy sector, particularly during the early stages of the transition. As reflected in the UK Hydrogen Strategy [2], the government has long-term commitments towards realising visions for a national hydrogen economy [34,67]. However, the potential importance of hydrogen to energy security ambitions and climate change targets should be better publicised, amid ongoing geopolitical, socio-economic, and environmental crises [13,68,69].

Ultimately, strengthening trust mechanisms across different parts of society, as inferred by the notion of public trust or 'social trust', holds significant potential for raising domestic hydrogen acceptance over the long-term. In the interim, a sectoral focus on increasing trust levels may prove imperative to building support for the national hydrogen economy and wider net-zero agenda, which involves strengthening trust in the government and energy sector [63].

It follows that public trust is an important precondition to enabling receptivity towards the promised socio-economic and environmental benefits of hydrogen homes [70,71]. Moreover, this thesis contends that public trust is critical to supporting the necessary enabling conditions for facilitating social acceptance, as indicated in Fig. 4-3 and Fig. 4-4. Stakeholders such as GDNOs, boiler manufacturers, and the Health and Safety Executive (HSE) can actively strengthen public trust by maximising efforts to safeguard environmental health and human safety in the context of domestic hydrogen.

At the same time, the role of the media [72,73], and specifically, the growing power of digital communication platforms [74,75], cannot be overstated in shaping socio-technical imaginaries for the hydrogen economy [33,76,77] and associated narratives around climate change [78,79]. It is through the mechanism of public discourse and principally digital communication via media outlets (whether traditional or social media) that the social representation of hydrogen homes will take shape. Critically, this thesis has shown that the underlying image of hydrogen will significantly influence prospects for social acceptance (see Fig. 3-5).

Cultivating a desirable vision – or socio-technical imaginary – for domestic hydrogen will hinge firmly on the reliability and efficacy of consumer-oriented research in reflecting the aspirations of end-users. Fine-grained insights and statistical findings – supported by qualitative approaches and quantitative analyses within a mixed-methods research paradigm – are needed to accentuate hopes for a sustainable domestic hydrogen future, grounded in social fairness and energy justice [80]. Foremost, visions for a low-carbon domestic hydrogen future [81] will rest on developing a rich understanding of public perceptions [82–84], and moreover, engaging consumers in the transition process [29,61].

Both sides of this equation can be supported by increasing the prevalence of consumer-oriented research [85], including focus groups, deliberative workshops, stakeholder interviews, survey studies, and ideally, longitudinal studies. By seeking to understand consumer attitudes and preferences during the early stage of the domestic hydrogen transition, net-zero actors can steer society towards a more optimistic energy future, which internalises reflective consumer engagement and deliberative policy making [86,87].

6.1.2 Targeted measures for supporting domestic hydrogen acceptance

The final sub-sections complete the discussion by focusing specifically on the technological and environmental dimensions of domestic hydrogen acceptance. Both dimensions are among the foremost areas that should be targeted to support the prospect of deploying hydrogen homes. Notably, technology perceptions also relate to safety aspects and financial expectations for purchasing hydrogen home appliances, whereby consumers seek to secure a relative advantage over existing gas appliances, in addition to evaluating comprehensive perceived effects (see Fig. 2-18). Additionally, environmental perceptions subsume part of the discussion around perceived community benefits (i.e. environmental benefits) and comprehensive perceived costs (i.e. environmental risks), as conceptualised in see Fig. 2-18.

6.1.2.1 Prioritising hydrogen heating over hydrogen cooking

Scott and Powells [88] flagged the likelihood that most consumers will perceive hydrogen cooking to be more disruptive and less desirable compared to heating. However, few studies have accounted for these dynamics in follow-up work [89,90]. Triangulating the findings from this thesis provides critical insights that can be leveraged by policy makers and other key stakeholders in the hydrogen actor-network.

Foremost, Chapter 5 showed that hydrogen boiler performance (M = 7.05) is perceived more favourably across the sample, compared to hydrogen hob performance (M = 6.21), as illustrated in Fig. 5-5. Moreover, all consumer sub-groups perceive the potential relative advantage of hydrogen boilers as superior to hydrogen hobs (see Fig. 5-5 and Fig. 5-7). Leveraging the results reported in Chapter 5, Fig. 6-1 and Fig. 6-2 confirm that consumers have an expressed preference for hydrogen heating over hydrogen cooking (see Fig. 6-3), while technology and environmental engagement, and to a lesser extent fuel stress, appear to drive support for both technologies.

Based on the modelling results, it emerges that hydrogen cooking could be supported by a sizeable portion of the UK population (i.e. the BLG). However, millions of households experiencing fuel poverty or high levels of fuel stress [13,65], alongside growing numbers of technology engaged and environmental conscious citizens [91], may prove less enticed by the prospect of switching to hydrogen cooking, which may also reflect safety concerns flagged in Fig. 3-10.

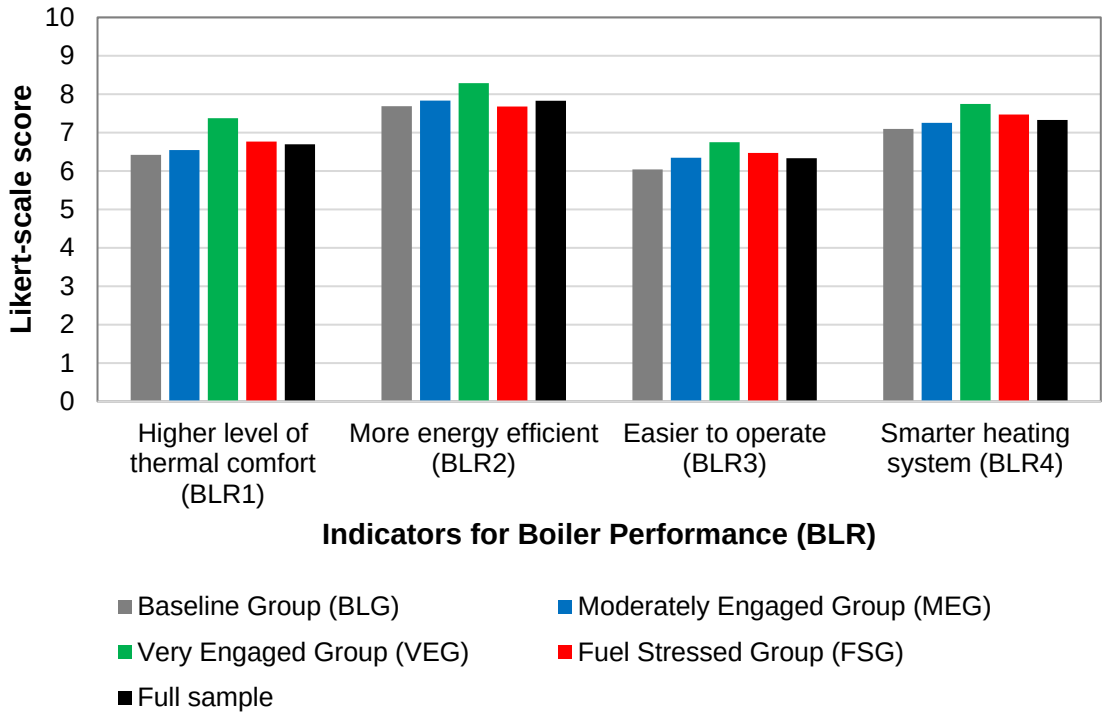

Fig. 6-1. Perceptions of hydrogen boilers across consumer sub-groups.

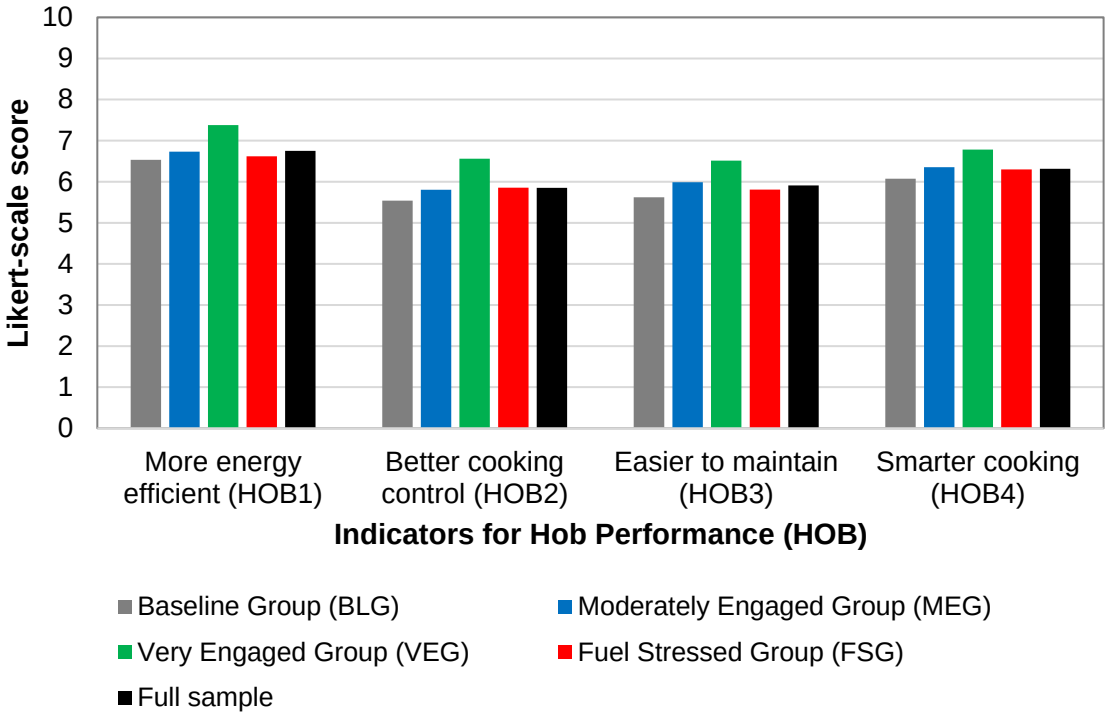

Fig. 6-2. Perceptions of hydrogen hobs across consumer sub-groups and full sample.

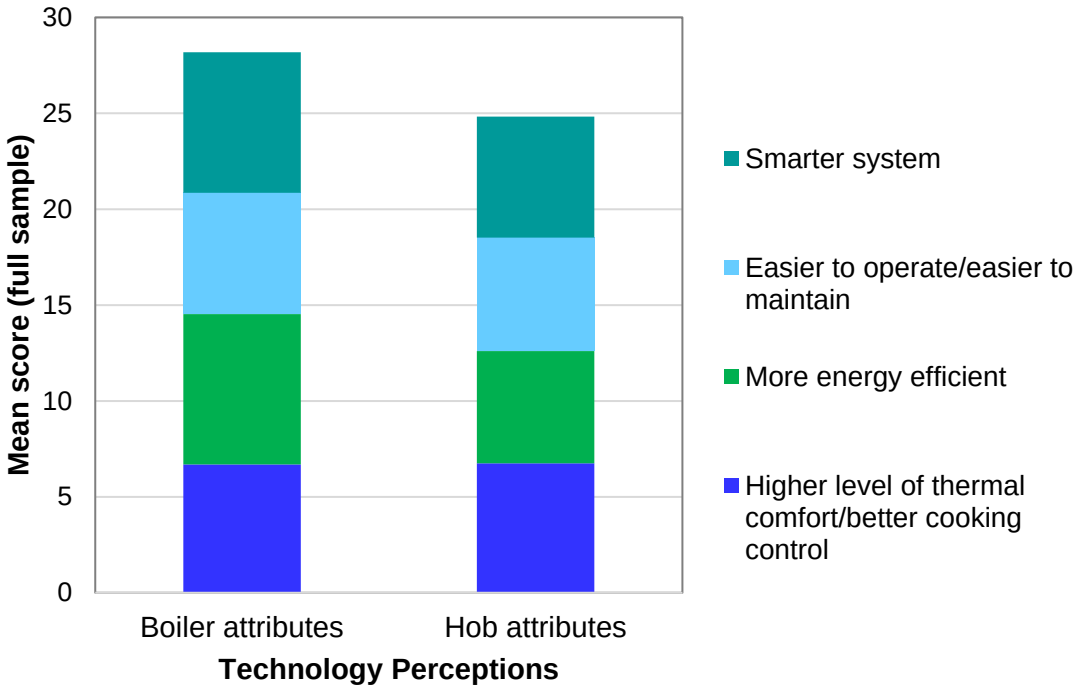

Fig. 6-3. Technology perceptions across full sample.

In view of the divergence between the Baseline Group (BLG) and remaining sub-groups, techno-economic and market factors [34] should guide a more conclusive decision on the configuration of the domestic hydrogen transition. As documented by Khalid and Foulds [92], induction hobs accounted for 24% of the UK market share for household cooking appliances in 2017.[1] Critical to this discussion, compound annual growth rate (CAGR) forecasts for portable induction hobs in the UK (~6.6%) are comparable to other major economies such as the United States, Japan, China, and South Korea [93].[2]

These growth dynamics are partially reflected by technological advances [94] and changing energy cultures [95], linked to growing awareness about energy efficiency and sustainable consumption [96–98]. In sum, the market for induction hobs is experiencing exponential growth [99–101], with companies such as Bosch, Electrolux, and Siemens holding the largest market share in Europe [99].[3] It follows that market

[1] More up-to-date figures on the growth of the induction hob market could not be reliably sourced for reporting within this discussion.
[2] The global market for portable induction hobs experienced a CAGR of 7.3% between 2018 and 2022, with forecasts suggesting a CAGR of 6.8% between 2023 and 2033 [98].
[3] Notably, several of companies manufacturing induction hobs (e.g. Worcester Bosch group) are also leaders in the heat pump market, which is forecasted to experience a CAGR of 11.1% between 2023 and 2028

dynamics dictate the likelihood of accelerated diffusion for induction hobs across the UK housing stock.

Notably, the UK Hydrogen Strategy [2] makes just five references to hydrogen cooking, whereas heating receives over 400 mentions, which has been reflected in government studies with a mostly heat-centric focus [23,102]. Furthermore, from a climate change perspective, cooking accounts for around 2% of total UK carbon emissions, compared to around 14% for domestic heating [92]; most of which is attributed to gas boilers [103,104].

In view of the evidence base, the case for supporting hydrogen cooking is relatively weak from a social acceptance perspective, and extremely weak when accounting for the underlying policy landscape, national and global market dynamics, as well as environmental factors. By contrast, the necessity of exploring a range of technology adoptions for heating, including hybrid heat pumps [105] – "combining an electrically-driven heat pump with a gas boiler, along with a dedicated controller" [106] – is significantly more justified from a climate change perspective.

Consequently, hydrogen heating holds more prospects for securing widespread social acceptance and may be able to diffuse at scale in upcoming decades. Overall, this thesis arrives to the following recommendation: policy makers and appliance manufacturers should hedge their bets on supporting hydrogen heating, while electrical appliances are better positioned – from a market, social, and environmental perspective – to replace gas appliances as the energy transition progresses.

6.1.2.2 Shifting perceptions of hydrogen production pathways

The environmental dimension of domestic hydrogen acceptance represents a focal point of interest within this thesis, as reflected by the inclusion of environmental engagement as a categorical filter in the multigroup analysis. Critically, leading academics have cast doubt over the viability of domestic hydrogen on environmental grounds [107]. Foremost, a 'blue' hydrogen pathway – contingent on steam methane reformation and carbon capture and storage (CCS) – has been subject to substantial criticism [108,109].

Findings from the focus groups analysis (see Appendix E) caution that parts of the UK public may see the twin-track production strategy [2] as non-committal to mitigating climate change, describing the approach as "*half-hearted*", "*half-baked*" or a "*half-way*

house." At one level, this perspective stems from concerns raised over blue hydrogen production in view of its uncertain environmental impacts and underlying climate change risks [108,110,111].

At the same time, the twin-track framing appears a root cause for scepticism, as reflected by the following perspective, "*…if they are really going to invest in it, they have got to do it fully…it's like with electric cars, they've only done it half-way*." At present, evidence suggests the inferred equivalence or balancing of the twin-track approach is unrecognised by the public, which obscures the apparent commitment towards ensuring complementarity over competition in realising the hydrogen economy [34].

Results from the online survey emphasise the apparent non-persuasiveness of the twin-track approach (see Fig. 4-3 and Fig. 5-10). Respondents expressed stronger support for green hydrogen production (M = 6.86) over blue hydrogen production (M = 6.17). However, support for the twin-track approach (M = 5.68) was below both individual pathways, which held true across all sub-groups (see Fig. 6-4). Synthesising the main findings leads to the following conclusion: in the context of hydrogen homes, implementing a blue hydrogen production pathway presents a greater social acceptance risk factor than a green pathway.

Foreseeably, this finding may correspond to the broader context of national hydrogen economies, as reflected in recent studies suggesting strong public support for a green pathway [18,112]. While blue hydrogen is likely a necessity for achieving industrial decarbonisation [113], and may underpin the foundations of developing national hydrogen economies in countries such as the UK [2], Germany [114], Australia [115], and Japan [116], qualitative and quantitative results reflect the need to deliver a clear and direct communication campaign to the public. In response, UK policy makers and key stakeholders should aim to promote the synergistic effects of scaling up different hydrogen production methods to support the country's net-zero targets [5], industrial strategy [117], energy security ambitions [118], and levelling up agenda [119].

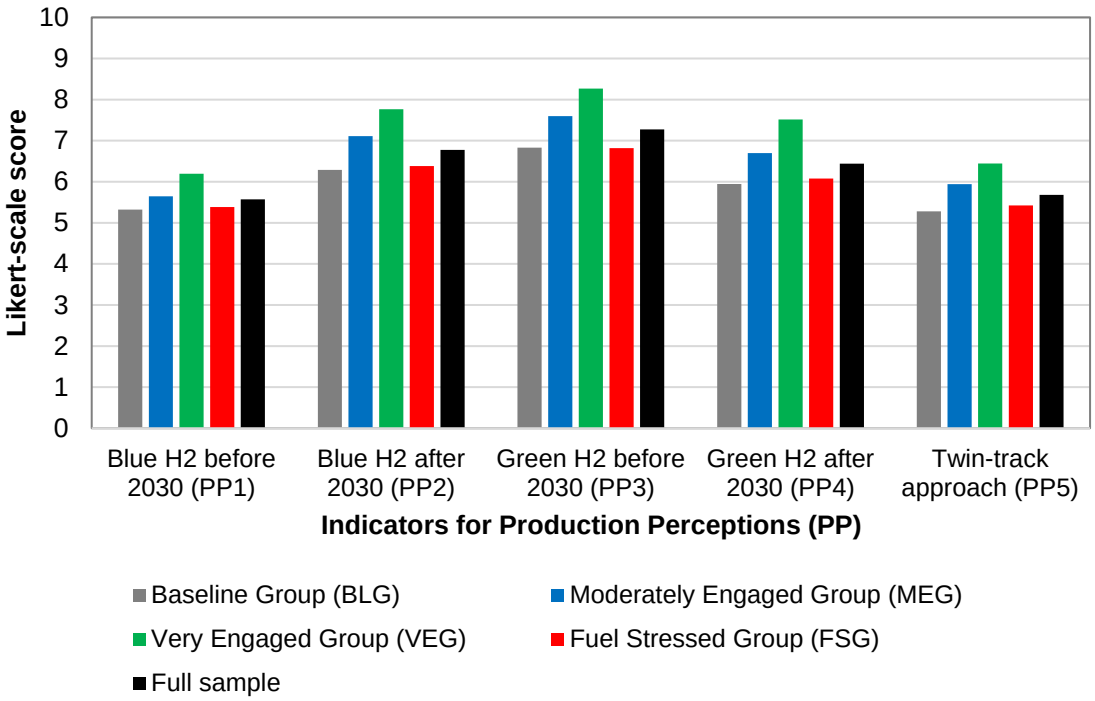

Fig. 6-4. Production perceptions across consumer sub-groups and full sample.

While the climate change credentials (e.g. global warming potential) of hydrogen production pathways remain a subject of debate among the scientific community [120–123], the UK government can respond by revisiting its decision to cast the production strategy in terms of a 'twin-track' framing. The main recommendation of this thesis, which may serve as a stepping-stone to raising acceptance prospects for domestic hydrogen, lies with dispensing with the notion of a twin-track production approach, in view of its propensity for raising confusion, doubts, and scepticism among the public.

Critically, 'multi-regime interactions' [124,125] between the gas industry and the renewable energy sector could stimulate synergies through symbiosis [34], which promote public trust in the transition [63,126] and support visions for a net-zero society [127]. Recasting the twin track approach and justifying the role of blue hydrogen to the public present important starting points for facilitating social acceptance. In doing so, the government can take strides towards building knowledge and awareness of hydrogen across society and supporting social trust in the hydrogen economy.

6.1.2.3 Leveraging opportunities for segment-specific strategies

Recent failure to secure community acceptance for hydrogen village trials can be partly attributed to context-specific dynamics; including the distribution of fuel stressed

households, and relative prevalence of technology and environmentally engaged consumers, within a given area such as Whitby.

Notably, in the context of electric vehicles, it has been shown that environmentally concerned citizens and innovative consumers in the Netherlands are more likely to have a stronger adoption intention [128], which also proved the case in this study. Energy acceptance findings in the Dutch context may prove especially relevant to the domestic hydrogen transition, since both the Netherlands and the UK share similar conditions in seeking to decarbonise the residential sector [129]. Critically, in accordance with findings in the literature (see Section 5.3.2), research carried out during this PhD project indicates that interest and engagement in environmental issues such as climate change, knowledge and awareness of renewable energy technologies, and interest in being an early adopter of new energy technologies will positively influence domestic hydrogen acceptance (see Appendix G).

During the formative stage of the domestic hydrogen transition, market choices are likely to involve a direct trade-off in prioritising a range of factors such as technology performance and community benefits, while also evaluating the importance of unpredictable factors such as financial costs [130]. Foremost, implementing hydrogen village trials across different regions of the United Kingdom may rest strongly on communicating the potential for economic, social, and environmental benefits at the community level [70,71,131], which is widely acknowledged in the energy acceptance literature [132].

PLS-SEM results (see Chapter 3) and findings from mixed-methods data analysis (see Chapter 5) affirm the extent to which domestic hydrogen acceptance will rest on securing meaningful environmental benefits, in addition to bringing socio-economic benefits to local communities [70]. However, as the transition progresses and consumers accumulate different levels of knowledge and awareness, it emerges that the influence of different factors may change significantly. It follows that cognitive factors – represented in this thesis by knowledge and awareness – may prove as significant as perceived community benefits in determining consumer willingness to adopt domestic hydrogen appliances before 2030.

At the same time, affective factors may prove decisive in establishing the level of adoption intention, which suggests both emotional response and rational thought will

play an influential role in shaping the prospecting market diffusion of hydrogen boilers and hobs, as suggested in Chapter 3 (see Fig. 3-7 and Fig. 3-12). Nevertheless, it should be borne in mind that productions perceptions and safety perceptions are influential factors throughout the innovation-decision process, albeit to varying degrees and to different extents for consumer segments.

In parallel, it has been shown that the foremost near-term priority for increasing adoption potential across the general population lies with strengthening technology perceptions of domestic hydrogen, since this construct held the most influence across the Baseline Group (BLG), as shown in Fig. 5-11 and Fig. 5-12. By contrast, production perceptions and perceived community benefits are more pronounced drivers across other consumer sub-groups.

6.1.2.3.1 Enter the hydrogen acceptance matrix

To supplement the ranking scheme, a novel contribution is presented in the form of the ‘domestic hydrogen acceptance matrix’, as captured in Fig. 6-5. The proposed matrix enhances the analysis presented within empirical chapters by mapping positive, neutral, and negative consumer attitudes towards hydrogen homes across a dynamic spectrum. Moreover, the visualisation provides an accessible means for stakeholders to readily gauge the current configuration of domestic hydrogen acceptance in the UK in relation to different consumer sub-groups.

Additionally, the presented matrix reflects the respective factors which influence domestic hydrogen acceptance and adoption potential at the sub-group level, thus supporting opportunities to pursue segment-specific, consumer engagement strategies. Specifically, each consumer sub-group is allocated an approximate position on the matrix, thereby demarcating zones of domestic hydrogen acceptance and resistance, as well as neutrality or potentiality. Reflecting the results presented in Chapter 3 (see Fig. 3-12 and Fig. 3-13) and Chapter 5 (see Fig. 5-8, Fig. 5-11, and Fig. 5-12), there are clear divisions between the respective sub-groups.

Foremost, the Very technology and environmentally Engaged Group (VEG) is more closely aligned to hope and optimism, while the Moderately technology and environmentally Engaged Group (MEG) is comparatively less optimistic yet still hopeful and curious. Similarly, the Fuel Stressed Group (FSG) transmit feelings of hopefulness which are characterised by a higher degree of cautiousness than

curiosity. Finally, the BLG is outright the most cautious, pessimistic, and sceptical sub-group.

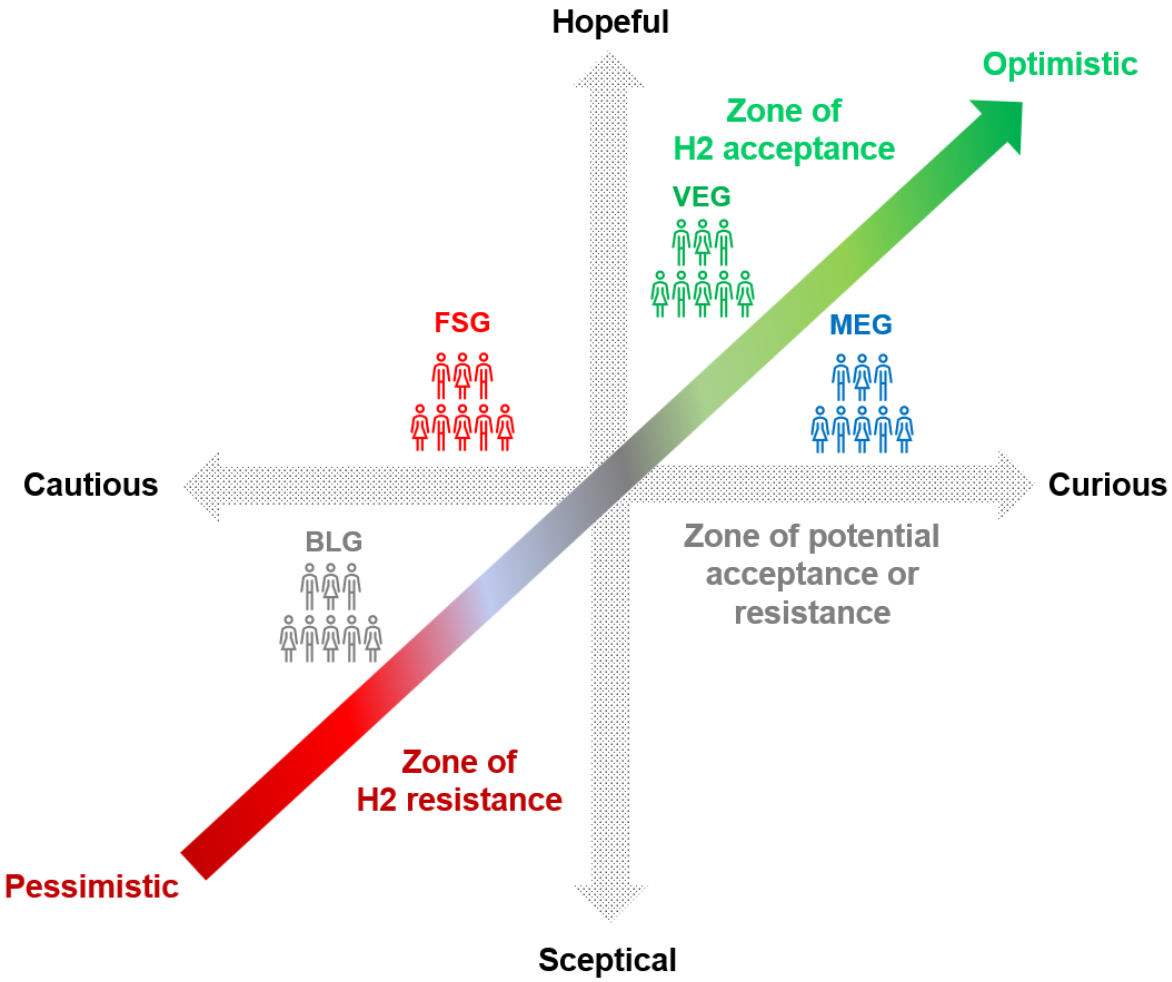

Fig. 6-5. Location of consumer sub-groups on the domestic hydrogen acceptance matrix.

Internalising the likely influence of factors identified within this PhD thesis can enable stakeholders such as GDNOs to reassess the locations which they target for local trials, in parallel to securing fundamental requirements such as proximity to energy inputs and industry. In an ideal scenario, it has been shown that a sub-population with high levels of technology and environmental engagement has a stronger propensity to support hydrogen homes, while fuel stress may act as positive mechanism to an extent.

There is an underlying imperative to ensure a more targeted and coordinated approach on the ground and in policy prescriptions, ahead of investing resources in the domestic hydrogen transition. This recommendation aligns to the formulation of Lei at al. [133] for “common but differentiated household mitigation policies” in the

Chinese context,[4] which is equally relevant to the context of residential decarbonisation in the UK. As a starting point, further consideration of spatio-temporal dynamics can help guide robust policy sequencing [134].

Through analysis of focus groups data (see Appendix D–E), qualitative responses to an open-ended question (see Chapter 3), and online survey data (see Chapter 5), this thesis shows that property owners responsible for investment decisions around cooking and heating technologies possess divergent preferences and expectations for transitioning to hydrogen homes [33]. The immediate implications of these findings are clear: key stakeholders within the public and private sector should account for the dynamics of consumer heterogeneity when devising strategies to support residential decarbonisation. Critically, accounting for heterogeneous household preferences can help mitigate the risk of devising ineffective, one-size-fits-all energy policies [135–137]. Furthermore, embedding the importance of consumer heterogeneity into social science research can help facilitate a more strategic understanding of market acceptance dynamics to support climate policies [33,138].

In practice, the prescribed shift entails embedding segment-specific strategies into policy making decisions, as opposed to limiting the focus to place-specific policies [139]. This calibration is needed to avert a situation wherein hydrogen trials are targeted in areas with potentially low levels of consumer acceptance, which proved at least partly true in the case of both Whitby village [140,141] and Redcar [142,143]. In view of the findings presented in this thesis, evidence-based measures grounded in a segment-specific approach should be implemented to alleviate concerns and worries over the prospective transition to low-carbon hydrogen homes.

This PhD project was shaped by the need to recognise and comprehend the dynamic nature of social acceptance, alongside the potential for heterogenous consumer preferences, ahead of long-term policy decisions. Consequently, the theory-driven data-grounded approach demonstrated in this thesis provides a research blueprint for informing socially acceptable transition pathways in the residential context.

[4] i.e. energy-saving policies in the urban China.

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7 GENERAL CONCLUSIONS AND RECOMMENDATIONS

This thesis was motivated by the need to identify, test, and validate the salient predictors of domestic hydrogen acceptance and adoption potential, while also accounting for potential divergence in acceptance and adoption dynamics between consumer sub-groups of the UK population. Through a mixed-methods convergent research design[1] which integrated multigroup analysis – each chapter made a distinct contribution to delivering these objectives to support consumer engagement strategies, deployment pathways, and policy making for residential decarbonisation. Chapter 7 closes the dissertation by summarising the findings of each thesis objective, highlighting the contributions to the literature, acknowledging the limitations of the study, and outlining a future research agenda for advancing scholarly engagement with the domestic hydrogen acceptance. Lastly, Section 7.5 provides concluding remarks and reflections on the research findings.

7.1 Fulfillment of thesis objectives

The **first objective** of this thesis was to *develop a conceptual framework to examine the dynamics of domestic hydrogen acceptance and prospective* adoption. This objective was fulfilled through a combination of outputs presented in Chapter 2, which undertook an integrative, comparative review of studies on hydrogen energy acceptance (N = 33) and domestic energy acceptance (N = 42) to develop a unified theory of domestic hydrogen acceptance.

The **second objective** was to *establish an empirically-grounded typology of domestic hydrogen acceptance and determine the factors which explain consumer heterogeneity*. Extensive analysis was undertaken on qualitative responses (N = 1064) to an open-ended question which concluded the online survey. Through a series of data transformation procedures, a comprehensive typology consisting of 48 sub-factors of domestic hydrogen acceptance[2] was developed in Chapter 3, demonstrating different drivers and barriers for respective consumer segments.

The **third objective** involved *constructing and validating a structural equation model to determine the salient predictors of domestic hydrogen acceptance across the UK population*. An online survey was deployed between October and December 2022 (N

[1] As supported by a sequential exploratory approach within the wider PhD project (see Fig. 1-2).
[2] Attributed to one of twelve 'core' factors.

= 1845) to support data analysis in SmartPLS 4.0; employing partial least squares structural equation modelling (PLS-SEM) to draw statistically supported conclusions on domestic hydrogen acceptance, as reported in Chapter 4.

The **fourth and final objective** corresponded to *constructing and validating a structural equation model to determine the salient predictors of domestic hydrogen adoption potential across sub-groups of the UK population*. Drawing on data from the online survey, Chapter 5 reported results from partial least squares multigroup analysis (PLS-MGA), which focused on examining the statistical differences in domestic hydrogen adoption potential between four consumer segments of the UK population.

Collectively, the fulfilment of each objective contributes towards the aim of informing consumer engagement strategies, deployment pathways, and policy making to support a socially acceptable transition to hydrogen homes, as discussed in Chapter 6. Specifically, the presented results can serve to strengthen momentum towards enacting a socially acceptable transition to hydrogen homes, should the techno-economic case for domestic hydrogen be made.

7.2 Contributions to literature

This thesis was constructed to accomplish specific conceptual and empirical contributions to the literature on domestic hydrogen acceptance and adoption, thereby supporting the wider social science research on national energy transitions and technology diffusion. The following sub-sections outline the main contributions of the thesis, while Table 7-1 summarises the specific contributions of each chapter.

7.2.1 Advancing a unified theory of domestic hydrogen acceptance

This PhD project was conceived in view of a theoretical knowledge gap on the topic of hydrogen acceptance [1], particularly in the context of residential decarbonisation [2]. In response, this thesis set out to develop a unified theory of domestic hydrogen acceptance, which is the foundation of this scholarly contribution. The proposed framework is rooted in seminal and recent theoretical contributions to the literature (see Fig. 2-2) and grounded in empirical insights from the literature on hydrogen acceptance and domestic energy acceptance, as reviewed in Section 2.4 (see Table L-6 and Table L-7).

Through an integrative, comparative review of quantitative studies across both literatures, Chapter 2 implemented an innovative research approach for extracting critical insights on domestic hydrogen acceptance. Foremost, Chapter 2 advances a comprehensive conceptual framework for examining the acceptance and adoption dynamics of hydrogen homes, which was formalised by operationalising 13 specific constructs, as identified via literature review (see Fig. 2-7 and Fig. 2-12). Drawing inspiration from predecessors such as the Unified Theory of Use and Acceptance of Technology (UTAUT) [3] and the Sustainable Energy Technology Acceptance (SETA) model [4], the unified theory presented in Fig. 2-18 accounts for the cognitive and emotional dimensions of human perceptions in predicting consumer attitudes and behavioural intentions toward hydrogen home appliances.

Through its multi-dimensional character and robust foundations, the framework developed in Chapter 2 holds substantial capacity to increase the predictive power of models. Whereas energy acceptance scholars such as Huijts et al. [4] demonstrated the efficacy of drawing directly on two theoretical foundations, namely, the theory of planned behaviour (TPB) [5] and the Norm Activation Model (NAM) [6], the unified theory proposed in Fig. 2-18 also leverages constructs from Diffusion of Innovation (DoI) theory the Technology Acceptance Model (TAM) [7], the UTAUT [3], alongside risk perceptions literature [8,9], trust-based models [10–14], and models integrating affective constructs (i.e. emotions) [15–18], in addition to energy acceptance frameworks [19,20].

The empirical contribution of Chapter 2 involved quantifying several new metrics, including the extent to which technological perceptions, financial perceptions, and comprehensive perceived benefits are underexplored constructs in hydrogen acceptance studies. Additionally, the study quantified the extent to which community acceptance is the least under-represented dimension across both hydrogen and domestic energy studies. Furthermore, the study demonstrated that, on average, between 2017–2023, hydrogen acceptance studies have engaged with less than 7 acceptance constructs ($M = 6.67$). The empirical findings motivate the need for deeper multi-dimensional engagement with domestic hydrogen acceptance.

7.2.2 Establishing an empirically-grounded typology of domestic hydrogen acceptance

Chapter 3 implemented an innovative analytical approach to hydrogen acceptance research through extensive coding of qualitative data, which facilitated statistical analysis following a series of data transformation techniques. Marking a critical juncture in mixed-methods research on hydrogen acceptance, a data-driven, hybrid deductive-inductive approach to thematic analysis was developed to examine consumer heterogeneity. The study demonstrated the efficacy of this technique to analyse the homogeneity within and the heterogeneity between consumer sub-groups, as supported by rigorous coding of qualitative data, thematic analysis, quantification of identified codes, and analysis of variance tests.

Chapter 3 presents a conceptual innovation by advancing an empirically-grounded typology of domestic hydrogen acceptance, demarcated according to a range of positive, neutral, and negative factors. The proposed typology is composed of 12 'core' factors of domestic hydrogen acceptance, which correspond to 48 'sub-factors'. Through statistical analysis, the study showed that *knowledge deficit*, *environmental benefits*, and *financial risks* are the most prominent sub-factors, and explain the most variance in response patterns. Additionally, six other sub-factors had statistically significant differences between certain consumer sub-groups (see Fig. 3-12 and Table 3-11).

Chapter 3 contributes to the literature by illustrating that consumers with a high level of technology and environmental engagement are more likely to express positive feelings about hydrogen and less likely to share negative emotions (see Fig. 3-12). Several factors contribute towards this response pattern: lower perceptions of financial risks; stronger expectations for environmental and energy security benefits; a lower knowledge deficit concerning hydrogen; minimal preoccupation regarding a perceived choice deficit; and limited concern over the cost-of-living crisis when forming an attitude towards hydrogen homes, among other factors (see Fig. 3-13).

As a result, Chapter 3 pinpoints the critical success and resistance factors shaping the dynamics of domestic hydrogen acceptance, while underscoring areas of convergence and divergence between respective consumer segments.

7.2.3 Validating the Domestic Hydrogen Acceptance Model

Chapter 4 applied partial least squares structural equation modelling (PLS-SEM) to test a baseline model, which operationalised domestic hydrogen acceptance and willingness to adopt domestic hydrogen as endogenous constructs (see Fig. 4-4). The model tested six specific acceptance dimensions via ten exogenous constructs to identify which action-orientated approaches may best strengthen social acceptance and subsequent adoption prospects for hydrogen homes. Critically, this contribution marks the first application of PLS-SEM to a dataset on domestic hydrogen, in addition to importance-performance map analysis (IMPA), which had yet to feature in a hydrogen acceptance study.

The proposed model explains 66.9% of the variance in domestic hydrogen acceptance across the sample. Additionally, the model demonstrated a moderate level of out-of-sample predictive power, which suggests the reported findings can reliably inform future decision-making on the domestic hydrogen transition. Perceived Community Benefits (PCB) proved the strongest predictor at the construct level (β = 0.276, ρ < 0.001), with *perceived environmental benefits* representing the most significant indicator (β = 0.121, ρ < 0.001). Additionally, respondents shared an expressed preference for green hydrogen over blue hydrogen production, as further discussed in Chapter 6 (see Fig. 6-4).

Furthermore, the results show that social acceptance positively and significantly predicts willingness to adopt domestic hydrogen appliances (β = 0.628, ρ < 0.001). Additionally, the analysis provides critical evidence regarding the ways in which acceptance and adoption dynamics are liable to change as consumers move through the innovation-decision process (see Fig. 1-3). As shown in Fig. 4-4, cognitive factors (energy awareness and subjective hydrogen knowledge) have a non-significant influence on domestic hydrogen acceptance, as well as non-significant indirect effects on willingness to adopt hydrogen appliances before 2030. However, when the relationship is tested within an alternative model whereby adoption intention is the sole endogenous construct, a significant and positive effect is observed in both cases (AWR: β = 0.054, ρ = 0.006; KNW: β = 0.132, ρ < 0.001). Notably, public trust is a positive and significant predictor of domestic hydrogen acceptance (β = 0.212, ρ < 0.001), but has a non-significant direct effect on adoption intention (β = -0.004, ρ = 0.856).

Through comparative analysis, Chapter 4 advances the hydrogen futures literature by empirically validating the positive and negative antecedents of consumer acceptance and adoption intention for hydrogen homes. While prior research identifies a range of factors and provides a mix of qualitative and descriptive findings [21–23], Chapter 4 develops a robust quantitative evidence base which can be built upon in follow-up studies.

7.2.4 Validating the Safety-Technological-Economic-Environmental Perspectives Framework and advancing multigroup analysis

Chapter 4 employed partial least squares multigroup analysis (PLS-MGA) to examine group-specific differences between four consumer segments of the UK population. This output marks an important milestone in the energy acceptance literature by pioneering a more nuanced approach to multigroup analysis. Critically, the study compares sub-groups comprised of different levels of technology and environmental engagement, while also including fuel stress as a categorical filter; thereby supporting the objective of informing socially acceptability and equitable transition pathways. As a result, a focus on social fairness was elevated by engaging with the notion of a 'just energy transition' [24–26] via the research design. Accordingly, Chapter 4 marks a significant extension to prior conceptual engagement with low-carbon energy adoption, which has typically been limited to comparing two segments (i.e. environmentally engaged and non-environmentally engaged).

Chapter 4 also demonstrates the validity of measuring domestic hydrogen adoption potential in terms of willingness to adopt domestic hydrogen appliances and perceived community benefits. The approach illustrates the viability of evaluating adoption potential through a hybrid measure of behavioural and community acceptance, which may be tested in other contexts such as support for hydrogen transportation.[3] Moreover, the efficacy of the Safety-Technological-Economic-Environmental Perspectives (STEEP) Framework is shown; explaining 53.5% of the variance in domestic hydrogen adoption potential for the full sample, with similar levels of moderate in-sample predictive power across sub-groups (R^2 = 0.478–0.539; *M* =

[3] For example, attitudes towards hydrogen fuel cell vehicles and hydrogen fuelling stations could be measured according to adoption intention and perceived community benefits.

0.514). Furthermore, the model exhibited high out-of-sample predictive power when tested on the FSG, while other sub-samples displayed moderate predictive power [27].

Across the full sample (N = 1845) (see Fig. K-2 and Fig. K-3), Production Perceptions was the strongest predictor in the model (β = 0.324, ρ < 0.001), followed by Safety Perceptions (β = 0.277, ρ < 0.001), and Technology Perceptions (β = 0.250, ρ < 0.001). However, at the sub-group level, statistically significant differences were detected in five of the six pairwise comparisons. The exceptional case was between the FSG and MEG. Notably, when compared to the full sample, Technology Perceptions (β = 0.352, ρ < 0.001) proved the most significant predictor of domestic hydrogen adoption potential for the BLG, followed by Production Perceptions (β = 0.265, ρ < 0.001), and Safety Perceptions (β = 0.220, ρ < 0.001). The study marks an important empirical contribution by demonstrating areas of convergence and divergence between different sub-groups, which can help to inform consumer engagement strategies and policy recommendations, as outlined in Chapter 6.

Table 7-1. Summary of conceptual and empirical contributions to literature.

	Contributions to literature	
Chapter	**Conceptual**	**Empirical**
Two (Publication 7)	• Develops a unified theory of domestic hydrogen acceptance ➢ **Fig. 2-18** • Systematically evaluates 13 constructs to increase the multi-dimensionality and predictive power of domestic hydrogen acceptance models ➢ **Fig. 2-16** • Integrates the cognitive and emotional dimensions of human perceptions in predicting the acceptance and adoption dynamics of hydrogen homes ➢ **Table 2-3**, **Table 2-4**	• On average, between 2017–2023, hydrogen acceptance studies have engaged with less than 7 acceptance constructs (*M* = 6.67) ➢ **Fig. 2-17** • Quantifies the extent to which technological perceptions, financial perceptions, and comprehensive perceived benefits are underexplored constructs in hydrogen acceptance studies ➢ **Fig. 2-7** and **Fig. 2-12** • Quantifies the extent to which community acceptance is the least under-represented dimension across both hydrogen and domestic energy studies ➢ **Fig. 2-15**
Three (Publication 9)	• Develops an empirically-grounded typology of domestic hydrogen acceptance, demarcated according to a range of positive, neutral, and negative factors ➢ **Fig. 3-4**, **Fig. 3-5** • Demarcates between primary, secondary, and tertiary 'core' factors and 'sub-factors' of hydrogen acceptance ➢ **Fig. 3-6, Fig. 3-7, Fig. 3-10, Fig. M-3**	• Identifies 12 'core' factors of domestic hydrogen acceptance, which correspond to 48 sub-factors ➢ **Table 3-3**, **Table 3-6**, **Table M-2** • Knowledge deficit, environmental benefits and financial risks are the most salient sub-factors and the foremost predictors of consumer heterogeneity ➢ **Table 3-6**, **Table 3-10**, **Fig. 3-7**, **Fig. 3-12**, **Fig. 3-13** • Consumer responses correspond equally to positive and negative acceptance factors ➢ **Table 3-5**
Four (Publication 10)	• Develops and tests a (baseline) Domestic Hydrogen Acceptance Model (DHAM) consisting of ten exogenous predictors ➢ **Fig. 4-1**, **Fig. 4-4** • The DHAM includes six distinct dimensions (cognitive processes, social capital, environmental attitude, risk perceptions, cost-benefit appraisal, and affective response	• The proposed model explains 66.9% of the variance in domestic hydrogen acceptance ➢ **Fig. 4-4** • The model demonstrates a moderate level of out-of-sample predictive power ➢ **Table 4-9**

	➢ **Fig. 4-1, Fig. 4-4, Table 4-7** • The DHAM tests the relationship between social acceptance and adoption intention ➢ **Table 4-6** • Enables direct comparison between acceptance adoption dynamics ➢ **Fig. 4-7, Table 4-8**	• Perceived community benefits is the strongest predictor in the model at the construct level (β = 0.276), with perceived environmental benefits representing the most significant indicator (β = 0.121) ➢ **Table 4-6** and **Fig. 4-6** • Environmental attitude is the most significant acceptance dimension, followed by social capital, affective response, cost-benefit appraisal, and risk perceptions ➢ **Table 4-7** • Cognitive processes are non-significant in predicting social acceptance, but have a positive and statistically significant direct effect on adoption intention ➢ **Table 4-10**
Five (Manuscript 2)	• Develops and tests the Safety-Technological-Economic-Environmental Perspectives (STEEP) Framework ➢ **Fig. 5-7** • Operationalises Technology Perceptions (TP) as a higher-order construct composes of perceptions towards Boiler Performance (BLR) and Hob Performance (HOB) ➢ **Fig. 5-11** • Performs a multigroup analysis with four sub-groups, implementing novel and targeted use of categorical filters to support the research aim and objectives ➢ **Fig. 5-11**, **Fig. 5-12**, **Table 5-1**, **Table 5-13**	• Group-specific differences are reported in all cases, except for between respondents with a moderate level of technology and environmental engagement (i.e. MEG) and non-engages respondents experiencing fuel stress (i.e. FSG) ➢ **Table 5-6**, **Table 5-11**, **Table 5-12** • The most significant divergence in adoption potential and respective drivers and barriers is observed between respondents with a high level of technology and environmental engagement (i.e. VEG) and non-engaged respondents who are not fuel stressed (i.e. BLG) ➢ **Fig. 5-11**, **Fig. 5-12** • Technology perceptions, production perceptions, and safety perceptions are the most heterogeneous constructs in the model ➢ **Table 5-12** • Financial perceptions is the least heterogeneous construct in the model ➢ **Table 5-12**

7.3 Limitations of research methods and empirical analysis

The work conducted within this PhD project contributes significantly to the body of social science research on national energy transitions [28–30], and specifically, consumer acceptance of residential decarbonisation via hydrogen in the UK context [31,32]. The outputs of the research are reflected through several publications in high-impact journals (see Fig. 1-1). Nevertheless, specific challenges led to some limitations in actualising the original research plan and executing the targeted analyses, as noted in Table 7-2. Although a few inevitable constraints were encountered during fieldwork, the adaptive research decisions reflect the implementation of an emergent mixed-methods approach, which was responsive to real-time developments as opposed to prescribed and rigid [33]. Comprehending the limitations of the work provides an important stepping-stone towards developing the future research agenda for engaging with the acceptance and adoption dynamics of hydrogen homes.

This PhD project entailed a strong emphasis on different research methods and analytical approaches, which supported deeper engagement with the topic through a mix of qualitative and quantitative analyses. Nevertheless, each research phase was subject to various limitations as reported in Table 7-2. In summary, Chapters 2 and 3 involved the researcher becoming “the instrument for analysis;” tasked with the responsibility of judging the codes and themes, and decontextualising and recontextualising the data [34]. As a result, the subjective nature of thematic coding means leaves the results open to subsequent iteration(s) in follow-up research, wherein other researchers may extract alternative findings from the data.

Specifically, in Chapter 3, the nature of subjective coding has a direct knock-on effect to correctly estimating the balance between optimistic and pessimistic responses via the associated latent factor approach. While these trade-offs are inherent to qualitative research practices, internalising the significance of such observations can help guide future studies. Furthermore, the research design implemented for the online survey was subject to certain constraints, which called for an adaptive sampling strategy. The challenges encountered during different research stages – including the online focus groups – are documented in more detail in Appendix Q, whereas Table 7-2 focuses on the empirical chapters composing the thesis.

Table 7-2. Limitations of research phases and outputs.

Research phase	Chapter(s)	Key limitations and constraints
Conceptual framework phase	Two	• Limited number of studies on domestic hydrogen acceptance within the sample • Only quantitative studies are included within the integrative, comparative review • Factors are identified according to frequency of occurrence within studies, but effect sizes are not accounted for (i.e. weight and meta-analysis) • Other factors may be important but remain underexplored in the research to date • Not all studies in the sample employed a theoretical framework • Other frameworks other than seminal contributions or recent additions to the energy acceptance literature may be relevant and include additional insights
Acceptance Typology phase	Three	• Thematic coding depends on the subjectivity of the researcher • Coding challenges are amplified when the dataset is large • Not all responses mapped to a specific sub-factor, while some coding results presented cases of overlap • The response rate reduced from 65.7% to 57.7% once invalid responses were excluded • Elements of uncertainty are embedded in the research approach • The influence of information provision materials on results is challenging to evaluate and may bias specific responses • The representativeness of the sample is impacted by digital exclusion
PLS-SEM phase	Four and Five	• The original multigroup design could not be secured • A strictly ‘fuel poor’ sub-group was relaxed to a ‘fuel stressed’ group • The individual effects of technology and environmental engagement could not be directly evaluated • Specific constructs proposed within Chapter 2 (e.g. objectively knowledge) were excluded from the model due to a lack of reliability and validity • Some constructs (i.e. knowledge, awareness, and perceived socio-economic costs) had less than three indicators • Certain socio-demographic factors (e.g. income and age) lacked national representativeness • Configural invariance could not be established for the model presented in Chapter 4, which prohibited multigroup analysis • The influence of information provision materials on results is challenging to evaluate and may bias specific responses • The representativeness of the sample is impacted by digital exclusion

7.4 Future research agenda

Several promising research avenues can be explored in follow-up work. Foremost, in a post-COVID environment, a return to in-person focus groups can help support potentially richer and more inclusive engagement with members of the public. Notably, online engagement methods can inadvertently overlook segments of the population due to digital exclusion [35].

The notion of a digital divide between North and South [36], and urban and rural communities [37], is well documented in the UK context [38]. Digital, as well as social exclusion, often link to higher vulnerability to poverty [38], with scholars recently exploring emerging linkages between “energy system digitalisation, digital exclusion, and energy poverty” [39]. Accordingly, future engagement with members of the public should internalise these observations by accounting for digital exclusion, while ensuring a diversity of fuel poor participants, in addition to a stronger representation of citizens from rural areas. Relatedly, in-person research methods may facilitate different group dynamics [40], which may overcome instances of hesitancy or reluctantly to engage through an online platform such as Zoom (see Appendix D–F).

While focus groups may serve as “the most common qualitative research tool applied to understand consumer behaviour and identify possible areas of focus for product development,” other qualitative methods such as deliberative workshops and semi-structured interviews can provide additional research perspectives. As highlighted by Kurtaliqi et al. [41], qualitative approaches are a critical means for advancing the use of PLS-SEM, while also offering a range of advantages over quantitative methods when considered in isolation [42,43]. For example, deliberative workshops [28,44] may afford more streamlined opportunities to apply different methods of information provision, such as positive, neutral, and negative framings around the domestic hydrogen transition [45].

In an early contribution to the hydrogen futures literature [46], Zachariah-Wolff and Hemmes [47] showed that positively and negatively coloured information had opposite effects (in the expected direction) on hydrogen perceptions among Dutch respondents, while the effect of neutral information proved marginal. Critically, recent research conducted in Australia has shown that information provision increases support for

hydrogen energy, both for domestic applications and exportation [48], while similar results have been reported for biogas in the Australian context [49].

Follow-up research on hydrogen homes and the perceptions of the UK Hydrogen Strategy can substantiate the extent to which different types of scenarios and information framing [50–52] may potentially skew public perceptions. Although previous studies on hydrogen perceptions have tested the effect of information provision by deploying large-sample surveys [45,47,48], this line of research can be successfully enacted within a workshop setting, as demonstrated by Fylan and colleagues [53] in the context of the H21 Leeds City Gate Project [54].

Information provision materials may be designed to support retrieval of (near-term) longitudinal data, thereby ascertaining the extent to which participants adjust their attitudes through learning and acquisition of new knowledge. This may be achieved in an accessible way by conducting polls at the start of the focus groups (or workshop), thereby establishing attitudes towards hydrogen homes prior to direct engagement with the topic. Subsequently, the same or modified versions of the initial poll(s) can be run towards the conclusion of the session, as a means of verifying how perceptions may have shifted.

By the same token, opportunities to engage with the same set of participants at different points in time will support more nuanced insights on the dynamic nature of social acceptance [55]. For example, online focus groups conducted during this project coincided with Russia's invasion of Ukraine [56,57], but just prior to the government's policy response via the British Energy Security Strategy [58].

Critically, the strategy doubled the 2030 hydrogen production to 10 GW and made commitments that at least 50% should be produced via electrolysis [58]. It is probable this detail would have influenced observed levels of concern and confusion expressed by some certain focus group participants regarding the premise of twin-track production approach [59]. Foreseeably, the updated target would support more favourable perceptions among parts of the public, such as environmentally engaged citizens. Accordingly, extracting evidence from longitudinal datasets within an emergent national context such as heat decarbonisation in the UK [60,61] provides a critical missing link to evaluate the influence of context-specific, macro-level factors [62].

In view of the research challenges (see Table 7-2 and Appendix Q), researchers can implement adjustments when conducting online surveys or self-administered questionnaires. One notable opportunity is to selectively extract information on consumer attitudes and positions through structured engagement. As opposed to relying solely on an open-ended question at the end of the survey, future studies can instead present a text box at the end of specific question blocks. For example, after questioning respondents about their attitudes towards the twin-track approach, a text box can be provided to allow for further reflections. This approach can be selectively applied to meet research aims, for example, providing a text box after questions on trust in actors and stakeholders if positing a trust-based model.

By introducing this technique, in line with practical considerations of survey length and research budgets, future studies can extract more fine-tuned insights on specific aspects of domestic hydrogen acceptance, which can facilitate more comprehensive comparative analysis across specific factors. At the same time, an open-ended question at the end of the survey can still be retained, as a means for validating prior response patterns and extracting additional insights. Accordingly, a stronger balance is struck between guided and open-ended engagement with respondents, which can reduce the burden of research subjectivity and support correct specification of emergent themes.

In future survey studies, researchers can also seek to elicit consumer perspectives vis-à-vis the domestic hydrogen acceptance matrix through means of self-identification (see Fig. 6-5), whereby respondents evaluate their position (e.g. hydrogen optimist, hydrogen cautious etc.). Together with prior recommendations, this approach can increase participation levels from respondents, thereby addressing limitations around potential survey fatigue or lack of engagement. One fruitful area for future investigation is to explore where participants self-identify on the hydrogen acceptance matrix, when presented to them through an interactive visual media.

Encouragingly, PLS-MGA [63,64] is one of several powerful techniques which can be employed when using SmartPLS software [65] to derive policy insights and managerial implications in the context of energy technology acceptance [66–68]. PLS-SEM offers a suite of analytical tools for advancing quantitative engagement with domestic hydrogen acceptance, which can help overcome some of the limitations discussed.

The proposed applications are listed below and summarised sequentially in Appendix Q. Critically, the research community should internalise these suggestions with a view to comparing the predictive capabilities [69] of different hydrogen acceptance and adoption models. While this study focuses specifically on expanding the scope of PLS-SEM to the domain of hydrogen research, emerging methods such as machine learning [70,71] and artificial neural networking [72,73] should also be harnessed as complementary tools.

- Mediation analysis to test whether a mediator variable governs the underlying relationship between two constructs in the proposed model
- Moderation to test whether a third variable influences the strength or direction of a relationship between two constructs in the proposed model
- Necessary condition analysis (NCA) to identify necessary (but not sufficient) conditions for supporting domestic hydrogen acceptance and adoption
- Combined importance-performance map analysis (cIMPA)[1]
- Finite-mixture partial least squares (FIMIX-PLS) analysis and PLS prediction-oriented segmentation (PLS-POS) to test for unobserved heterogeneity
- Establishing higher-order models to increase the parsimony of the PLS path model, while increasing the bandwidth of potential indicators covered within respective constructs
- Comparing different models within the same analysis to better determine the salient predictors of domestic hydrogen acceptance/adoption and the predictive capabilities of proposed models

Subsequent multigroup approaches may include demarcating between technology and environmentally engaged respondents, as well as securing a stronger representation of fuel poverty within the sample. Additionally, multiple research avenues can be explored in future work. One option is to compare different jurisdictions of the UK [74] to gain deeper insights on public perceptions of hydrogen across England [21,22], Scotland [75], Wales [31], and Northern Ireland, or otherwise taking a sub-national approach to explore regional acceptance dynamics [67]. However, careful attention must be paid to ensuring that nationally representative quotas are secured for categorical variables.

[1] i.e. IMPA and NCA [106].

Provided that the necessary criteria are met to apply PLS-MGA,[2] future studies can compare respondents with different knowledge and awareness levels of hydrogen to derive insights on the influence of cognitive factors. Another important research pathway involves conducting cross-national comparative analyses to explore differences in domestic hydrogen acceptance across countries such as the UK [21,31], Germany [76], and Australia [45,48].

Additionally, scholars should aim to extend the evidence base on the hydrogen economy by further comparing public perceptions of different hydrogen energy technologies and production pathways [77–79]. At the same time, there is a growing imperative to compare public perceptions of different residential decarbonisation pathways in national contexts such as the UK, as recently highlighted by Becker et al. [60] and Thomas et al. [31]. A starting point is to build on the initial contribution of Williams et al. [80] through a more systematic analysis of domestic hydrogen and heat pumps, which can be supported through a rigorous mixed-methods approach, as exemplified within this thesis.

Finally, while this thesis focused exclusively on public perceptions, understanding the perspectives of other actors is critical for supporting strategic policy making and managerial decisions. Critically, the role of intermediary actors such as industry associations [81] and non-government organisations [82], as well as middle actors such as building professionals [83,84], will further shape the dynamics of trust and acceptance for hydrogen transition [85,86]. Similarly, as demonstrated by Lowes and Woodman [61], UK policy makers have somewhat divergent perceptions of UK heat decarbonisation, which may be more pronounced following recent developments around hydrogen homes.

In view of the complexity of the domestic hydrogen transition and diversity of the actor-network [62,85,87], qualitative research engagement with different stakeholders will enhance insights on the emerging configuration of domestic hydrogen acceptance and prospective technology diffusion. Notably, the need to leverage explicitly qualitative approaches is reflected in the seminal contribution of Mick and Fournier [88], which retrieved “the richest data” on technology perceptions in the residential context (e.g.

[2] Including (at least) partial measurement invariance via the MICOM, sample size requirements, and meeting thresholds for statistical power, as described in Section 5.6.3.

laptops, multimedia devices, dishwashers etc.) via phenomenological interviews, as opposed to questionnaires.

7.5 Concluding remarks and reflections

This PhD project commenced in late 2020, prior to the release of the UK Hydrogen Strategy in August 2021 [89]. This milestone was followed by the Heat and Buildings Strategy in October 2021 [90], ahead of the United Nations Climate Change Conference (COP26)[3] in Glasgow. Following Russia's invasion of Ukraine in February 2022 [91] – which coincided with online focus groups conducted during this project – the global political and economic context has shifted substantially [92,93]. The ensuing energy crisis [94] has motivated more stringent energy security ambitions and commitments to non-fossil resources among British policy makers [95] and European counterparts [96–98]. Notably, hydrogen has been promoted as a substitute fuel for natural gas, and as a mechanism for decoupling energy supply from Russian fossil-based imports [99–101]. Consequently, as documented in the final research output from the online focus groups stage [102], significant shifts have occurred at the macro-level during this PhD project.

Reflecting on this reality is critical to understanding the results in their wider context, while anticipating how the antecedents of domestic hydrogen acceptance and adoption may potentially shift in the future. Critically, it has been empirically shown that public trust is an important (positive) predictor of domestic hydrogen acceptance, although the construct has a non-significant direct effect on adoption intention. Foreseeably, should the landscape shift towards greater political and economic stability, it is likely that socio-political acceptance would increase [103]. It follows that consolidating a more optimistic energy future, as espoused by the candidate in [104] (see Appendix G), may be contingent on critical factors such as public trust and environmental engagement, which must surge to support 'hydrogen hopes' for UK homes [105].

[3] Conference of the Parties.

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APPENDIX A. Socio-technical barriers to domestic hydrogen futures: repurposing pipelines, policies, and public perceptions

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Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Conceptualisation, Writing – review & editing, Supervision.

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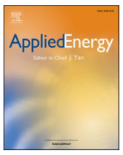

Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions☆

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HIGHLIGHTS

- Desirable hydrogen futures will rest on more than a repurposing of pipelines.
- Policymaking should couple techno-economic feasibility to social acceptability.
- Multi-regime interactions can enable synergies for blue and green hydrogen.
- Hydrogen backbones should be examined as a multi- and cross-scalar phenomenon.
- Socio-technical systems thinking supports an accelerated and just transition.

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ABSTRACT

The feasibility of the global energy transition may rest on the ability of nations to harness hydrogen's potential for cross-sectoral decarbonization. In countries historically reliant on natural gas for domestic heating and cooking such as the UK, hydrogen may prove critical to meeting net-zero targets and strengthening energy security. In response, the UK government is targeting industrial decarbonization via hydrogen, with parallel interest in deploying hydrogen-fueled appliances for businesses and homes. However, prospective hydrogen futures, and especially the domestic hydrogen transition, face multiple barriers which reflect the cross-sectoral dynamics of achieving economies of scale and social acceptance. Addressing these challenges calls for a deep

Abbreviations: ACO, Ant colony optimization; ADR, European Agreement Concerning the International Carriage of Dangerous Goods by Road; ASHPs, Air source heat pumps; ATEX, Equipment for explosive atmospheres; ATR, Auto-thermal reforming; ATR + CCS, Auto-thermal reformation with carbon, capture and storage; BEIS, Department for Business, Energy & Industrial Strategy; BEVs, Battery-electric vehicles; CV, Calorific value; CAPEX, Capital expenditure; CCC, Committee on Climate Change; CCS, Carbon, capture and storage; CCUS, Carbon capture utilization and storage; CGH_2, Compressed gaseous hydrogen; COMAH, Control of Major Accident Hazards; COP, Climate Change Conference of the Parties; CSP, Concentrated solar-thermal power; DECC, Department for Energy and Climate Change; DHT, Domestic Hydrogen Transition; DMS, Dimethyl sulphide; EC, European Commission; EHB, European Hydrogen Backbone; EU, European Union; ENA, Energy Networks Association; FBM, Future Billing Methodology; FID, Final Investment Decision; FIT, Feed-in-tariff; GAD, Gas Appliances Directive; GAR, Gas Appliances Regulation; GDNOs, Gas Distribution Network Operators; GDP, Gross domestic product; GHG, Greenhouse gas; GoO, Guarantee of Origin; GS(M)R, Gas Safety (Management) Regulations; GSHPs, Ground source heat pumps; HESs, Hydrogen Energy Systems; HETs, Hydrogen energy technologies; HFCVs, Hydrogen fuel cell vehicles; HyLAW, Hydrogen Law and removal of legal barriers to the deployment of fuel cells and hydrogen applications; H_2S, Hydrogen sulfide; IEA, International Energy Agency; IED, Industrial Emissions Directive; IES, Adoption of innovative energy services; IJHE, International Journal of Hydrogen Energy; IMRRP, Iron Mains Risk Reduction Programme; IPCC, International Panel on Climate Change; IRENA, International Renewable Energy Agency; LBD, Learning-by-doing; LCOH, Levelized cost of hydrogen; LCOT, Levelized cost of transmission; LHV, Lower heating value; LH_2, Liquid hydrogen; LOHCs, Liquid organic hydrogen carriers; LTS, Local Transmission System; MECs, Microbial electrolysis cells; MLP, Multi-Level Perspective; $MtCO_2$, Metric tons of carbon dioxide; NIST, National Institute of Standards and Technology; NO_x, Nitrogen oxides; NTS, National Transmission System; Ofgem, Office of gas & electricity markets; OPEX, Operating costs; PE, Polyethylene; PEM, Proton exchange membrane; PV, Photovoltaic; PPC, Pollution Prevention and Control Regulations; P2H, Power-to-hydrogen; RETs, Renewable energy technologies; RHS, Renewable hydrogen-based systems; ROW, Right-of-way; RSER, Renewable & Sustainable Energy Reviews (RSER); SLO, Social licence to operate; SOEC, Solid oxide electrolysis cells; SMR, Steam methane reformation; SMR + CCS, Steam methane reformation with carbon, capture and storage; STS, Socio-technical systems; TMB, tert-Butyl mercaptan; TRL, Technology readiness level; TNT, Trinitrotoluene; TSOs, Transmission System Operators; TWh, Terawatt hour; T&S, Transport and storage; UKCS, UK Continental Shelf; UK HFCA, UK Hydrogen and Fuel Cell Association; UNC, Uniform network codes; UHS, Underground hydrogen storage; WI, Wobbe Index.

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understanding of socio-technical factors across different scales of the hydrogen economy. In response, this paper develops a socio-technical systems framework for overcoming barriers to the domestic transition, which is applied to the UK context. The paper demonstrates that future strategies should account for interactions between political, techno-economic, technical, market, and social dimensions of the hydrogen transition. In parallel to techno-economic feasibility, the right policies will be needed to create an even playing field for green hydrogen technologies, while also supporting stakeholder symbiosis and consumer buy-in. Future studies should grapple with how an effective repurposing of pipelines, policies, and public perceptions can be aligned to accelerate the development of the hydrogen economy, with maximum net benefits for society and the environment.

1. Introduction

Despite sustained scientific[1] and commercial[2] interest over several decades, hydrogen's promise as a revolutionary clean energy carrier has been largely characterized by 'false starts' [1] and 'false dawns' [2]. Hydrogen's shortcomings [3] are partly explained by high infrastructure costs for production, storage, and distribution; owing to its low energy density per volume, explosive characteristics, and ability to cause embrittlement in metals such as steel [1]. Indeed, the safety credentials of hydrogen have been debated for several decades [4–7] in relation to various sectors and applications [8], including transport, [9,10], power [11–13], industry [14,15], handling and storage [16–20], and more recently, residential use [21–23]. Consequently, hydrogen technology remains a contested topic [24], characterized by blurred representations between myths and facts [25], especially in relation to hazards and risks [4].

As an energy vector with multiple applications across a wide range of energy systems [26][3] hydrogen is highly coveted for its climate change mitigation potential [27,28]. Critically, hydrogen may provide large-scale electricity storage and load-balancing services [29]. In addition to supporting emissions reduction across industry and transport [30–32], hydrogen has also been recognized as a potential low-carbon substitute for natural gas, which may prove critical to decarbonizing the residential heating sector [33]. Hydrogen heating could present an important energy transition pathway in some of Europe's key markets, [34–36], especially those historically reliant on natural gas [37], such as the UK and Netherlands [38–40]. Notably, the Committee on Climate Change (CCC) envisions a role for hydrogen in decarbonizing the UK's residential sector as part of a low-carbon hybrid heating system aligned to net zero [41].

1.1. The UK Hydrogen Strategy

In the run up to the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow [42], the UK released its Hydrogen Strategy [43] followed by the Heat and Buildings Strategy [44], which built off the vision set forward in the Ten Point Plan for a Green Industrial Revolution [45]. As a forerunner to these strategies, the Scottish Government Hydrogen Policy Statement [46] exemplified the UK's push to be at the 'technology core' [47] of the global hydrogen economy. Taken together, these strategies support a 'no and low regrets' approach to developing hydrogen solutions for the residential sector,[4] while confronting "strategic challenges" to realizing a national hydrogen economy [43]. The UK government identified eight main barriers to developing a national hydrogen economy: policy and regulatory uncertainty; technological and commercial risk; production costs; lack of infrastructure; distribution and storage constraints; demand uncertainty; supply and demand coordination; and lack of market structure [43].

The UK Hydrogen Strategy envisions a 'twin track' production approach; combining large volumes of CCUS-enabled and electrolytic hydrogen to help future-proof the country's net zero ambitions by avoiding over reliance on a single technology pathway [43]. Guided by the twin-track approach, the UK hydrogen landscape is rapidly evolving to include a range of industrial, commercial, and domestic applications [43,48]. Following the release of the British Energy Security Strategy in April 2022 [49], the UK government has committed to at least 50% electrolytic hydrogen production (i.e. 5 GW), in parallel to a regional focus on the deployment of blue hydrogen hubs around industrial clusters [50,51].

Critically, the CCC forecasts that hydrogen demand will need to increase from 27 TWh in 2017 to 270 TWh by 2050 to enable the UK to meet its carbon target of net-neutrality by 2050 [52]. This decade, the bulk of hydrogen demand will come from industry (~10–21 TWh), with modest demand potential from the power (~0–10 TWh) and transport (0–6 TWh) sectors [43]. In contrast, demand for low-carbon hydrogen heating in buildings may be constrained to under 1 TWh. Evidently, the feasibility of hydrogen homes is contingent upon developments across other sectors, while the underlying "hydrogen socio-technical system" is embedded within the wider energy transition [26].

1.2. Re-envisioning the hydrogen economy

Against this backdrop of historic, current, and emerging barriers, there is renewed global interest and commitment towards realizing hydrogen's long-held potential for improving local air quality, mitigating climate change [53–55], strengthening energy security [56,57] and improving international competitiveness [55]. Capitalizing on the current "political and business momentum" towards realizing visions for a national hydrogen economy will require coordinated action on at least five fronts: policy frameworks; market structures; technology scale-up; infrastructure development; and costs reduction [58]. At the global level, developing a hydrogen economy will similarly rest on a minimum of five key levers: favorable policy frameworks that create a market pull; new national and international regulatory frameworks to address finance, tax, environment, and safety aspects; stakeholder engagement with public and private actors to deliver a roadmap; demand for energy storage and electricity grid balancing; and sustained commitment to reducing greenhouse gas (GHG) emissions and strengthening energy security [59].

1.3. Research gap, aims, and objectives

Although setbacks and barriers to the commercialization of hydrogen have long persisted [60], with certain aspects catalogued and explored by the research community [1,59,61,62], few studies have attempted to unpack the interactions between socio-technical factors shaping prospective 'hydrogen futures' [55]. Despite the imperative to decarbonize, potential barriers to the domestic hydrogen transition (DHT) remain underexplored [63]. Foremost, there remains an underlying knowledge gap regarding the interactions between respective socio-technical

[1] For example, machine learning research on hydrogen's physical properties [386] and its potential for energy storage [387,388] has its foundations in scientific work from the 1920s [389].

[2] The concept of a global 'hydrogen economy' can be traced back to at least the 1970s [390–392].

[3] See Fig. 44 in Griffiths et al. [26] for an illustration of hydrogen's role in the energy system.

[4] Included are plans for a hydrogen neighborhood and village trial by 2023 and 2025, and potential for scaling up to a hydrogen town trial in 2026 [43,44].

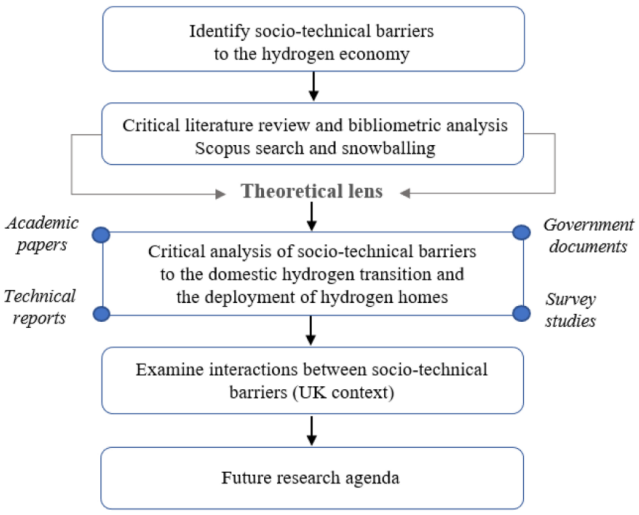

Fig. 1. Research procedure and methodology.

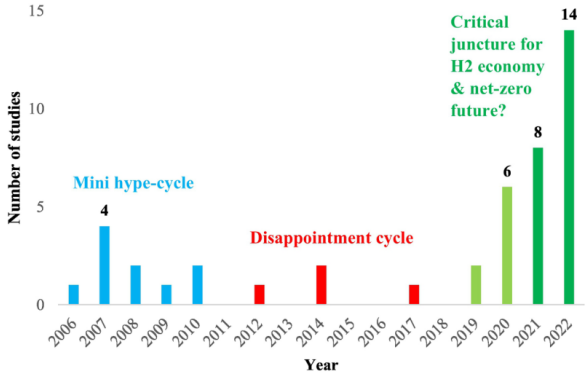

Fig. 2. Number of studies on barriers to the hydrogen economy, 2006–2022.

searches in different databases [81,82].[12] Snowball logic relies on identifying references or citations of interest within already retrieved literature [81,83].[13] This technique is effective for quickly gauging the richness of research materials associated with a given subject area [84] and efficient retrieval of relevant literature [85,86]. Compared to implementing specific search strings to perform a more systematic literature review (SLR), snowballing can help access valuable materials sourced from the grey literature [83,85].

From the academic literature, Section 4 drew on 109 articles with a specific focus on different barriers to the DHT, compared to 44 in the earlier review for building the theoretical framework (see Fig. 5). Of the 109 articles retrieved, 47 corresponded to the techno-economic dimension (43.1%), 30 to the technical dimension (27.5%), 6 to the political dimension (5.5%), 7 to the market dimension (6.4%), and 19 to the social dimension (17.4%). Accordingly, more grey literature materials were sourced to discuss soft barriers to the DHT, compared to techno-economic and technical barriers. Fig. 5 shows that IJHE is the dominant journal in both searches (see Table S4), which is consistent with findings in the bibliometric analysis performed by Kar et al. [72] (n = 1275).[14] IJHE holds around 40% of publications on the hydrogen economy [72], and leads in specific areas of research such as hydrogen storage [87] and microbial electrolysis cells (MECs) [88], making it the pioneer journal for this research field.

[12] These included Scopus, Web of Science, Google Scholar, and the Hydrogen Knowledge Centre.

[13] 'Backward' snowballing involves accessing the reference list of a selected article, while 'forward' snowballing relies on identifying studies that cite the selected article [82,396].

[14] See Fig. 7 in Kar et al. [72] showing "Clusters of journals publishing on hydrogen economy research."

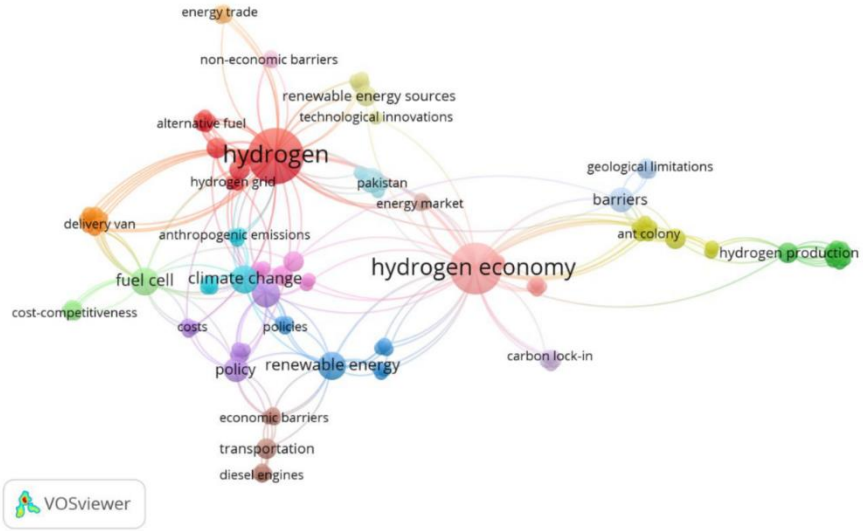

Fig. 3. Network visualization of keywords in Scopus dataset: co-occurrence threshold one.

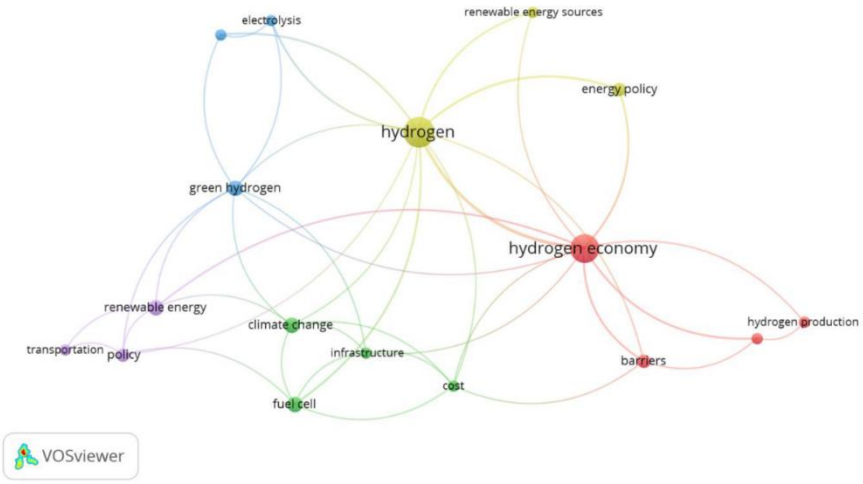

Fig. 4. Network visualization of keywords in Scopus dataset: co-occurrence threshold two.

Drawing on the dataset collected during the snowballing procedures (n = 109) (see Sections 2.2.1 and 2.2.2), the earlier procedures using VOS viewer were repeated. Setting the number of co-occurrences to one resulted in 261 connected items (327 total), made up of 24 clusters (see Figs. S2 and S3). By contrast, setting the number of co-occurrences at two resulted in 42 connected items spread across 14 clusters (see Fig. 6). The network visualization highlights emerging research areas aligned to market barriers (e.g. value chain optimization) and social barriers (e.g. public perception, social practices, and energy justice). This finding is consistent with some of the observations presented by Kar and colleagues [72], such as growing research on issues related to public safety.[15]

2.2.1. *Techno-economic and technical factors*

Techno-economic factors involve 'energy flows' related to

[15] See Fig. 9 in Kar et al. [72] for a comparison.

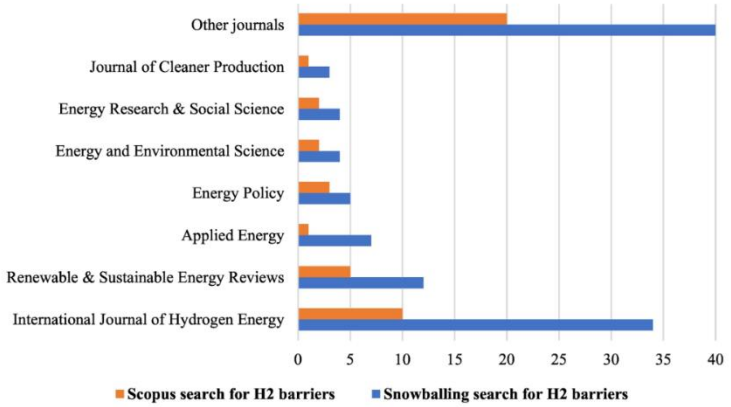

Fig. 5. Comparison between Scopus search and snowballing search for hydrogen barriers.

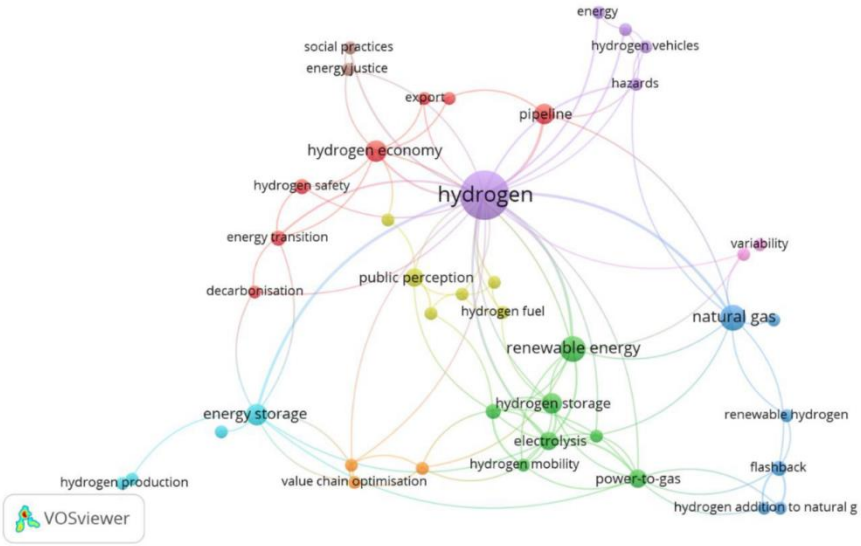

Fig. 6. Network visualization of keywords in articles retrieved through snowballing procedure: co-occurrence threshold two.

developments around resources and infrastructure [71], which following Crisan and Kuhn [89] represent the "hardware" of the hydrogen transition. Addressing this dimension, Section 4.1 draws on a range of studies analyzing data on various hydrogen production pathways and related techno-economic aspects. Several of these studies were retrieved from IJHE [59,90–92]. Following the snowballing procedure, other important materials were sourced from the academic literature [93–95], alongside reports from the International Renewable Energy Agency (IRENA) [96–98] and International Energy Agency (IEA) [57,99], government-led studies [43,49,100], and other key stakeholder groups shaping the hydrogen economy [101–104].

Relatedly, technical factors concern safety issues, the performance and efficiency of hydrogen appliances, and the impacts of hydrogen blending on pipelines. Section 4.2 investigates scientific findings on the technical and safety risks of injecting hydrogen into existing pipelines [105–107], and the results of experimental tests on representative natural gas cooktop burners running on hydrogen blends [108–110]. Hydrogen blending and appliance performance are further reviewed based on UK studies [111,112] and supporting international evidence [106,113,114]. To supplement materials on hydrogen safety factors recently reviewed by the authors [115], two separate keyword searches were performed in Google Scholar using the terms "blending hydrogen into the gas grid" and "hydrogen appliance safety." A highly cited study retrieved from IJHE [116] and Applied Energy Journal [110], respectively, were selected to initiate the snowballing process, which led to inclusion of several articles from these journals, alongside other findings in the academic and grey literatures.

2.2.2. Literature materials on political, market, and social factors

Evidence on political factors was mainly sourced through backward snowballing using the meta-review of Griffiths et al. [26] on industrial low-carbon hydrogen, which cited 718 studies. Section 4.3 reviews the scope of the HyLAW project [117], which aimed to reduce regulatory, legal, and administrative barriers to the development of a European hydrogen economy. Specifically, the HyLAW UK National Policy Paper [118] serves to contextualize the challenges associated with the current regulatory framework, or lack thereof, for hydrogen gas. Further evidence is sourced from government materials [112,119,120], trade bodies such as RenewableUK [121] and the UK Hydrogen and Fuel Cell Association (UK HFCA) [51], and other grey literature [123].

A wide range of factors impact the technology readiness level (TRL), market penetration and growth of domestic hydrogen [96], which can otherwise be viewed through the lens of barriers to market entry, development, and support [112]. Section 4.4 incorporates backward snowballing from the discussion of hydrogen home appliances provided by Scott and Powells [21,22]. Given the limited evidence base available in the academic literature, a specific search was also carried out in the Hydrogen Knowledge Centre database[16] to supplement the data collection through a combination of backward and forward snowballing.[17] In addition to work carried out by Policy Exchange[18] [123], extensive analysis of both political and market factors has also been undertaken by gauging the perspective of UK manufacturers and trade bodies [112].

Finally, accounting for the social dimension of the transition reflects a growing consensus that consumer acceptance is a precondition for the successful deployment of low-carbon energy technologies [124–128]. This dimension broadly reflects factors underpinning the social acceptance of established renewable energy technologies (RETs) [129–131]. Key factors include public perceptions of hydrogen's environmental and safety credentials, together with attitudes towards community-level and behavioral impacts [115,132]. The evidence base on domestic hydrogen acceptance is mostly limited to the UK [21,22], Australia, [23,67], and Europe [133–135]; composed of studies focused on the public's knowledge, awareness, and perceptions of hydrogen, and resultant attitudes towards the deployment of hydrogen homes [115]. Section 4.5 implements a backward snowballing approach based primarily on a recent literature review conducted by the authors [115].

3. Theory

This Section describes the theoretical foundations of the study. Drawing on key examples in the sustainability transitions literature, Section 3.1 introduces the socio-technical transition approach. Section 3.2 contextualizes socio-technical systems thinking to the hydrogen transition. Section 3.3 then summarizes the underlying barriers to developing a hydrogen economy. Finally, Section 3.4 focuses on the DHT and the case of hydrogen homes.

3.1. Socio-technical systems thinking on sustainability transitions

Socio-technical systems [65] develop through multi-decadal processes [136,137], taking shape through the co-evolution of a mix of interdependent technologies, infrastructures, institutions, policies, markets, supply chains, user practices, and cultural meanings [138–140]. Prime examples of large-scale systems serving the needs of society include housing, mobility, heating, and food [139].

Critically, sustainability transitions are 'non-linear' and 'complex' events; shaped by interactions between technological, political, institutional, economic, and socio-cultural dimensions, and through interrelationships between multiple actors [141]. For example, Cherp et al. [71] conceptualize national energy transitions according to the co-evolving dynamics of three types of systems, while Eyre et al. [142] discuss four "categories of change" for deep decarbonization (see Table S2). Adding to this multi-dimensionality, scholars have recently explored technology transitions through the lens of 'evolutionary', 'interpretive and socio-cultural', and 'contested, conflictual' processes [70].

The literature on 'socio-technical futures' – visions or scenarios predicated on prospective techno-scientific and societal change [143,144] – recognizes the governance of socio-technical systems as inherently political [144], with energy futures examined through a multi-level governance perspective [145,146]. Specifically, the "political feasibility" of climate mitigation pathways should be closely examined by contrasting political constraints, characterized as 'soft' and 'probabilistic' in nature, against technical constraints which are 'hard' and 'deterministic' [147]. Such perspectives highlight the purposeful nature of governing large-scale shifts to low-carbon technologies [148], as underpinned by recent country pledges to reach net-zero emissions [149].

3.2. Socio-technical systems thinking hydrogen futures

Reviewing the state of the hydrogen futures literature in the early 2000s, McDowall and Eames [55] highlighted a research gap regarding the socio-technical dynamics of the transition, owing to an underlying deficit in existing theoretical approaches. Addressing this theoretical gap, Eames et al. [24] explored the potential for a hydrogen economy in London by examining visions and expectations through the lens of six competing narratives. The authors concluded that visions of the hydrogen economy are subject to considerable 'interpretive flexibility' [24] – "the capacity of a specific technology to sustain divergent opinions" [150] – which may strengthen hydrogen's potential to compete across a wide range of energy futures [151]. Interviewing key stakeholders within the Danish hydrogen research network, Andreasen and Sovacool [152] similarly uncovered multiple visions for the technology, characterized by "strategic malleability" over which pathways to support and the likelihood of hybridized hydrogen systems. Despite these important contributions, the literature remains dominated by studies engaging with technology roadmaps and transition pathways, mainly limited to the context of hydrogen transport applications [153,154] (see Table S2).

3.3. Socio-technical factors shaping the hydrogen economy

Despite multiple driving forces [55,59], the hydrogen transition is yet to materialize due an array of barriers [1], which must be tackled in parallel to deploy hydrogen at scale [155]. While some of these factors have been discussed in different transition contexts (see Table S3), few studies have examined challenges of a socio-technical nature [63]. To date, techno-economic and technical factors impacting Hydrogen Energy Systems (HESs) have been reviewed in different contexts, such as HFCV technologies in the USA [156], hydrogen production methods in India [157], renewable hydrogen-based systems (RHS) for stationary applications, and renewable or 'green' hydrogen supply at the global level [158]. Several studies have also addressed barriers to developing a global or national hydrogen economy [1,59,61,96]. Nevertheless, there remain inconsistencies or even explicit absence regarding the breakdown of socio-technical factors [55].

For example, Balat and Kirtay [159] discussed the technical factors influencing the hydrogen economy in terms of production, storage, and

[16] https://www.h2knowledgecentre.com/

[17] Using the dropdown menu, the keyword "Hydrogen for Domestic Appliances" and country, "United Kingdom," returned 47 results. Having scanned the titles, the search was then narrowed to more recent publications since January 2018 (38 results) and subject matter "Policy and Socio-economics," which returned 13 results: eight policy papers, three research papers, and two journal articles. Having scanned the abstracts, backward and forward snowballing was conducted on six of these papers.

[18] The UK's leading think tank.

delivery costs. By contrast, in their discussion of power-to-hydrogen (P2H) systems in Italy, Saccani et al. [160] characterized technical factors in terms of "each component and/or the process as a whole that limit P2H efficiency, effectiveness, reliability and safety." The authors classified other factors according to economic, social, and normative/operational aspects [160], whereas without specifying any typology, Garcia [161] identified five non-economic barriers (NEBs) to the deployment of hydrogen technologies and infrastructures in Europe. In a recent perspective on the European hydrogen economy, van de Sperk et al. [155] also provided a comprehensive analysis of techno-economic, legal, and regulatory, and market aspects.

Notably, Griffiths et al. [26] provide an exception to these studies in classifying the hydrogen socio-technical system for industrial decarbonization according to five major areas – production, supply chain, industrial use, institutional drivers, and end-use drivers[19] – which the authors discuss systematically in terms of political, economic, social, and technical factors. Illustrating this diversity and lack of systematic framing, Table 1 summarizes key barriers identified in recent studies at the national, European, and global level.

3.4. Socio-technical factors shaping domestic hydrogen acceptance

Heiskanen et al. [166] were among the first to identify social acceptance factors of low-carbon hydrogen heating solutions according to the following parameters: hydrogen characteristics in terms of safety, cost, usability, convenience and (thermal) comfort; the national and local context; the robustness of supply chains and skilled technicians; and composition of stakeholder engagement. More recently, the feasibility of converting the UK's existing natural gas network to hydrogen has been assessed from a techno-economic perspective through the H21 Leeds City Gate study [167], but remains characterized by deep uncertainties [168]. Additionally, Dorrington et al. [112] identified multiple technical and market barriers to "the development of a hydrogen-fired appliance supply chain," based on the perspective of appliance manufacturers and trade bodies (See Section 4.4).

As with natural gas-based appliances [39], the socio-technical system for hydrogen homes will be sustained by a range of interdependent factors which may accelerate or stifle the transition. However, interactions between respective factors and associated barriers are yet to be examined in detail, characterizing hydrogen homes [169,170] as an underexplored subject in the energy transitions literature. As a way forward, the existing evidence base can be synthesized according to five distinct dimensions: political, techno-economic, technical, market, and social factors. Table 2 identifies each socio-technical dimension, its key factors, and respective parameters and enabling conditions, as operationalized to the context of the DHT. This contribution brings order and clarity to the wide range of impacts discussed across the literature by distinguishing more concretely between technical, economic, and market factors, which are sometimes subsumed under the 'techno-economic' category [71].

Drawing on the findings presented in Table 1 and Table 2, Fig. 7 proposes a socio-technical transition framework; visualized according to identified political [1,55,59,61], techno-economic [13,171,172], technical [55,59,60], market and social factors [55,61,158,160], which together shape the development of hydrogen infrastructure, supply chains, domestic appliances, and social acceptance. Having established a comprehensive socio-technical systems framework for examining the DHT, Section 4 provides a systematic discussion of each of these factors.

[19] Griffiths et al. [26] present an overview of the STS for industrial use of hydrogen in Fig. 9 and a high-level illustration of this framework in Fig. 10 of their study.

Table 1
Barriers to developing hydrogen energy systems and national hydrogen economies.

Study	Context	Scope of study	Barriers identified
[73]	Australia	Developing a national hydrogen economy and hydrogen society	• High cost of hydrogen • Lack of infrastructure • Technological immaturity • Insufficient investment • Low market readiness • Low social acceptance • Negative safety perceptions
[162]	Brazil	Developing a national hydrogen economy, with a focus on the development of a green hydrogen market	• Economic feasibility • Lack of political support and incentives for infrastructure and market creation/expansion • Development of appropriate regulation framework • Research & Development
[163]	China	Development of hydrogen fueling stations (HFSs)	• High initial capital costs • Limited financial channels • Immature hydrogen storage technology • Incomplete hydrogen transportation technology • Lack of relevant standards • Imperfect subsidy mechanism
[157]	India	Commercialization of hydrogen-powered vehicles	• Infrastructure development and delivery • Legislation and regulation • High costs of production, transport, and storage • Uncertainties concerning social acceptance
[164]	Qatar	Developing a multi-sector green hydrogen economy	• Large-scale hydrogen production cost • Infrastructure investments • Achieving bulk storage • Costs and feasibility of transport and distribution • Safety considerations • Matching supply-demand uncertainties
[160]	Italy	Market development for power-to-hydrogen (P2H)	• Efficiency, effectiveness, reliability and safety of components and processes • Impact of economic sustainability on market penetration • Public and individual levels of hydrogen awareness and familiarity
[165]	Eastern Europe[a]	Developing social acceptance of hydrogen as an alternative to traditional fuels	• Lack of public knowledge and awareness of hydrogen technologies • Public fears and insecurities concerning technological innovations and potential social/behavioral changes • Economic risks and increased energy costs

(continued on next page)

Table 1 (*continued*)

Study	Context	Scope of study	Barriers identified
[61]	Europe[b]	Deployment of hydrogen technologies and infrastructures	• Complex legal and administrative procedures among involved authorities • Lack of governments initiatives for increasing the transmission and distribution networks and the use of hydrogen vehicles • Lack of information and assistance to project applicants • Lack of regulations and guidelines for the installation of hydrogen systems • Absence of qualified specialists to manage hydrogen projects • Safety perceptions of the deployment of HESs and HETs
[26]	Global	Industrial utilization of low-carbon hydrogen for deep decarbonization	• Geologic carbon storage potential is geographically specific • CCS applications are expensive to develop and operate • Upstream emissions associated with fossil energy for blue hydrogen pathways are not properly considered • Technological immaturity with emerging hydrogen production technologies (e.g. high temperature electrolysis) still at low TRL • The cost of electrolytic hydrogen is still higher than existing fossil hydrogen pathways

Source: Author's compilation.
[a] Poland, Czech Republic, and Slovakia.
[b] Austria, Finland, Germany, Greece, Hungary, Italy, Norway, Poland, Portugal, Romania, Slovenia, Sweden, Ukraine, United Kingdom.

4. Assessment and analysis of socio-technical factors from a UK perspective

4.1. Techno-economic factors

Given its multi-sectoral applications [173], the role of hydrogen in different energy scenarios is often conflicting, with a lack of specific techno-economic evidence [174]. Following the example of van der Sperk et al. [155], this section provides a 'one-stop starting point' for understanding the techno-economic parameters of the hydrogen economy.

4.1.1. Hydrogen production

At present, 95% of global hydrogen production is sourced from fossil fuels [95,175]. Steam methane reformation (SMR)[20] accounts for nearly half of this production [95,175], while partial oxidation of natural gas and coal gasification account mostly for remaining production [176]. SMR is a mature technology which has been used for decades to handle large capacities of fossil-based ('grey') hydrogen production [177]. Alongside SMR, auto-thermal reforming (ATR)[21] and water electrolysis[22] are commercially mature technologies, capable of producing hydrogen at scale [33,178]. For SMR and ATR to be considered low-carbon or 'blue', high rates of carbon, capture and storage (CCS) are required (>90%) [43,177]. Alternatively, water electrolysis ('green' hydrogen) refers to the process of electrochemically splitting water into hydrogen and oxygen, through the application of renewable electrical energy [179].[23]

4.1.1.1. Hydrogen production costs. Despite widespread social and environmental implications [23], the trajectory of competing low-carbon hydrogen pathways may rest principally on cost factors [114,180]. Hydrogen production is a major factor determining overall system costs [181], which requires careful sensitivity analysis due to significant uncertainties [43,182]. While the costs of SMR are well known and modeled according to historical data, there are currently no operational CCS plants within the UK, which makes calculations less reliable [183]. At present, there is less literature on the costs of CCUS-enabled hydrogen compared to electrolysis production methods [182]. Overall, examining the costs and timeline of producing hydrogen is a nascent but growing research area.

Table 2
Socio-technical factors to the deployment of hydrogen homes.

Dimension	Key factors	Key parameters and conditions
Techno-economic	• Resource availability • Production, transport/ transmission, and storage pathways, • Associated cost factors	• Configuration and scale of hydrogen energy infrastructure and scope of project development
Technical	• Safety levels (health and environmental) • Efficiency, reliability, and overall performance hydrogen home appliances	• Practicality of deploying hydrogen energy infrastructure and domestic technologies to meet all engineering, safety, and environmental standards
Political	• Policy measures, regulatory frameworks, legislation, and administrative procedures • Stakeholder engagement and informational flows	• Enabling legal pathways to support a national hydrogen economy and transition to hydrogen homes, predicated on procedural justice
Market	• Investment landscape and market risk • Labor supply and quality of this workforce • Other supply- and demand-side factors	• Competitiveness and commercial feasibility of hydrogen technologies and supply chains for home appliances
Social	• Safety, environmental, and cost perceptions • Social fairness • Behavioral impacts	• Consumer attitudes towards the domestic hydrogen transition and broader hydrogen economy, as shaped by public awareness, knowledge, stakeholder trust, and other social acceptance factors

Source: Authors' compilation.

[20] Chemical synthesis process for producing syngas from hydrocarbons, whereby steam and natural gas react catalytically at high temperature and pressure [176,194].

[21] Combines endothermic (steam reforming) with exothermic (partial oxidation) reactions within the same reactor [397].
[22] Alkaline electrolyzers consist of electrolyzer cells combined in parallel to build an electrolyzer stack [193].
[23] Alkaline electrolyzers are commercially viable (TRL 9) at the lowest cost; proton exchange membrane (PEM) electrolyzers are nearing commercialization (TRL 8–9); solid oxide electrolysis cells (SOEC) are still under development (TRL 5–6) [217,398]; while biomass-based advanced gasification technology with CCS is at TRL 4–5 [399–401].

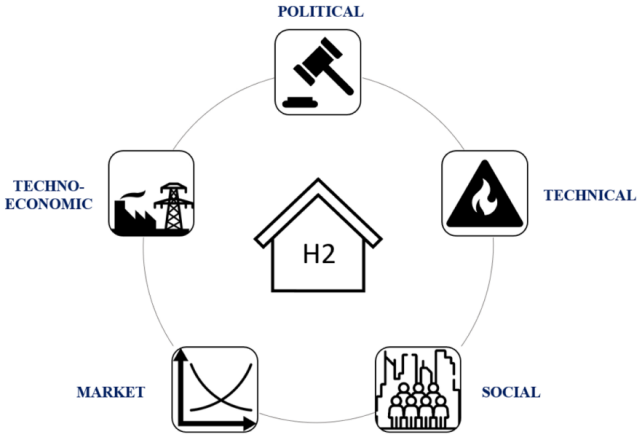

Fig. 7. Socio-technical transition framework for the domestic hydrogen transition.

Although estimates remain tentative [114], the costs of producing and storing large-scale hydrogen are likely to be very substantial [41]. The CCC estimates that decarbonizing heat for buildings through hydrogen and/or electrification could amount to 0.7% of gross domestic product (GDP) in 2050 [41], with hydrogen production potentially increasing the annual costs of heating by around £4 billion [41]. Deloitte UK estimate that hydrogen production technologies alone will require at least £3.5 and up to £11.4 billion by 2035 [183]. Considerable infrastructure investment and engineering capacity are required for developing hydrogen-based technologies [63,112]. Additionally, significant investment is needed to increase testing facilities where hydrogen is produced on-site, while supporting product diversification and efficiency gains [112].

4.1.1.2. Barriers to a blue hydrogen pathway. Fuel costs represent the largest component of hydrogen production costs [57].[24] SMR depends on large quantities of methane (CH_4) [95]; making the natural gas price a major component of overall production costs for blue hydrogen [34]. Coinciding with the COVID-19 pandemic, multiple economic and geopolitical factors [184] caused the price of natural gas to skyrocket in the UK from 36 pence per therm to 290 pence per therm between March and October 2021 [185]. During times of gas crisis, the production costs of blue hydrogen will rise steeply as a direct knock-on effect [186]. Several other factors determine the economics of hydrogen production via SMR: the cost of the reformer; transport and storage (T&S) costs; CO_2 recovery costs; and operational costs for utilizing natural gas reformation together with carbon capture and storage (CCS) [114]. Based on a net-zero scenario, CCS could account for 26%–40% of the total costs for blue hydrogen production [183].

SMR + CCS may accelerate the development of a hydrogen economy by capitalizing on the existing supply chain for natural gas, which can be repurposed for hydrogen production, storage, and distribution. To establish this market, at least three conditions must be satisfied: hydrogen infrastructure to link points of production and consumption; CCS infrastructure to pipe (or ship) the carbon dioxide (CO_2) to storage sites; and large-scale and sustained hydrogen demand [114]. Thus, the economics of a SMR plant depend partly on the CO_2 capture rate [177]. Given that CCS is yet to be commercialized at scale [114], there are multiple unknowns and cost considerations for a blue hydrogen pathway. Notably, storage costs remain highly uncertain and will vary according to geologic location [26,187].[25] Meanwhile, extensive infrastructure will be required to transport CO_2 from inland sites, which will require sizeable investments [114].

At present, the feasibility of establishing a national hydrogen economy partially based on SMR + CCS [180,188] is constrained by the progressive depletion of domestic gas reserves in the UK Continental Shelf (UKCS) [189], as reflected by the country's status as a net importer of energy since 2004 [190]. Increased natural gas imports would be needed to address this supply gap [190,191]. Alongside these challenges, fuel conversion inefficiencies need to be addressed for blue hydrogen production [176].

4.1.1.3. Barriers to a green hydrogen pathway. Water electrolysis may offer an alternative pathway to achieving large-scale renewable hydrogen production with lower carbon emissions [192] and negligible downstream waste [114]. Electrolytic hydrogen can be deployed in proximity to areas of high renewable resource to increase local production from grid-connected electrolyzers [114]. Although more attractive from an environmental perspective and for decentralized applications, especially in proximity to areas of high renewable resource [114], there are also multiple challenges to scaling up electrolytic hydrogen. Barriers include high production costs, lack of value recognition, energy losses and sustainability challenges [98].

Electricity price determines 60%–80% of green hydrogen cost [193], adding to potential market volatility and investment risks. Green hydrogen production costs are driven mainly by the high CAPEX associated with the cost of the electrolyzer [183], which requires high capital investment [181]. Furthermore, converting hydrogen fuel into mechanical or electrical energy is constrained by maximum efficiencies of 50%–60% [176]. The round-trip efficiency of hydrogen is between 15%–30%, therefore, green hydrogen production requires 4–5 times more electricity production compared to direct transmission [194].

[24] Excluding hydrogen produced from coal. For a recent review of hydrogen production costs, see [59] and [158].

[25] The 2016 Department for Energy and Climate Change (DECC) report provided a median cost of £19/tCO_2 for transportation and storage, with high and low sensitivity costs of £31/tCO_2 and £8/tCO_2, respectively [187].

While electrolyzer plant costs remain high, they are expected to fall over time with the experience curve and economies of scale [193].[26]

The UK's offshore wind resource presents an opportunity to scale up renewable hydrogen production [195], with scope for hydrogen hubs in proximity to coastal, industrial clusters [196,197], and export potential to parts of Northern Europe such as Germany, Netherlands, and Belgium [46,198]. Supporting this opportunity and the wider transition to net zero, the UK government has increased its offshore wind target to 50 GW [49] and aims to capture 10 Mt. of CO_2 by 2030 [45]. However, the resource demands for building a national hydrogen economy could prove especially difficult to surmount if an estimated 100–150 GW of gas reforming capacity with 175 $MtCO_2$ per year – equivalent to 300 GW of offshore wind power dedicated to electrolysis – is needed to meet 800 TWh of demand across multiple applications [199].

Overreliance on offshore wind power could jeopardize the feasibility of securing economies of scale for the UK's green hydrogen production base within a net-zero time-horizon. In addition to the uncertainties associated with spatio-temporal variability [200,201], scaling up offshore wind capacity is subject to external factors beyond the UK's borders [202], which may leave the country vulnerable to meeting its renewable targets. Prospects are further compounded by the government's stance towards onshore wind planning [49], which remains hostile and unambitious compared to offshore wind targets. In 2016, the Conservative Party withdrew public subsidies for onshore wind and granted decision-making powers to local communities, which resulted in an effective moratorium [203,204]. Although the British Energy Security Strategy boosted the offshore wind target from 40 GW to 50 GW by 2030, onshore wind policy failed to "introduce wholesale changes to current planning regulations," thereby extending the status quo by leaving "local communities in control" [49].

4.1.2. Hydrogen pipeline construction and transportation

At present, hydrogen pipelines span less than 16,000 km globally [26,174] compared to around 3,000,000 km for conventional gas pipelines [158], highlighting the extreme experience deficit for hydrogen projects. Unlike renewable energy projects such as wind farms and concentrated solar-thermal power (CSP) which have benefited from learning-by-doing (LBD)[27] [205], the economics of hydrogen pipelines are volatile and may fail to reap cost reductions over time [206].

In addition to miscellaneous costs, the construction costs of hydrogen pipelines depend on three main factors: material requirements, labor costs, and right-of-way (ROW) fees [206,207]. All cost categories decrease as transmission length increases, except for ROW cost which remains largely fixed [194]. Schoots et al. [206] found the labor costs of hydrogen pipelines would be 28% higher than natural gas due to more challenging operating conditions [206]. Overall, the construction costs of hydrogen pipelines may exceed that of CH_4 and CO_2 by approximately 19% and 8% [206]. Compared to gas pipelines [63], hydrogen pipelines are more capital intensive as they require greater diameter [208], and are likely to incur higher costs due to greater requirements for compression at several stages of the supply chain, welding procedures, and leak testing [209]. While cost reductions are achievable by minimizing changes in flow velocity between compression stations,[28] the CAPEX and transport costs of hydrogen remain at least marginally higher than natural gas [194] (see Table S6) and can be substantially higher [206,210].

Compressed gaseous hydrogen (CGH_2) can be transported via pipelines, whereas trucks and ships can move CGH_2 or liquid hydrogen (LH_2) [92]. CGH_2 trailers are optimal for small quantities transported over distances up to 200 km, while LH_2 trailers are more economical for smaller volumes and longer distances [92]. However, liquefying hydrogen is an energy-intensive and costly process [92], which makes transport by pipelines a more feasible solution. Furthermore, the transport of hydrogen in the UK is currently restricted, with exclusions on ten tunnels that have category C, D, or E limits on the transit of ADR[29] substances which include hydrogen [118]. While category A tunnels (lowest risk) may be used at any time, category B tunnels may have time restrictions in place, further impeding the logistics of hydrogen transportation. Moreover, there are limitations on the volume and pressure of high-pressure receptacles used to transport hydrogen by road, which makes it unfeasible to deliver bulk hydrogen to large-scale end users [118].

Transport costs are a key component of energy transition pathways, especially when considering scenarios for blue or green hydrogen deployment [194]. Hydrogen transport costs depend on the volume transported, the distance, operating pressure, and pipeline diameter, which are determined by hydrogen mass flow and pressure drop [211,212]. Investments in infrastructure (e.g. pipelines, trucks, ships) should also be added when calculating operational costs (OPEX) [41]. Hydrogen has a comparatively low volumetric density[30] compared to naturals gas,[31] which means that larger volumes will be needed to transport the same amount of energy [158].[32] Although OPEX costs are low, pipeline transport is subject to high capital investment costs at limited flow rates [211]. Using a baseline case of 1000 miles, DeSantis et al. [194] calculated the costs of hydrogen pipelines to be 40% higher than natural gas (See Table S5), while Saadi et al. [210] also estimated that the relative costs of hydrogen pipeline transport would be higher compared to gas pipelines.

4.1.2.1. Repurposing the gas grid to hydrogen. Following the launch of the Iron Mains Risk Reduction Programme (IMRRP) in 2002 [43,213], there is growing interest in repurposing the UK's existing gas network to support hydrogen applications [167]. The IMRRP addresses the failure of 'at risk' iron gas mains, which are to be converted to polyethylene (PE).[33] Critically, PE is a potentially viable material for transporting hydrogen at low pressures within the gas grid over the long term [34,214]. In parallel to the IMRRP, the UK government together with the country's gas distribution network operators (GDNOs) are testing the feasibility of both hydrogen blends and a 100% conversion to hydrogen [43,167,215]. Most notably, Project Union could establish a 2000 km hydrogen backbone linking major industrial clusters and carrying at least 25% of current UK gas demand [215].[34] However, the feasibility of this scenario rests on the scale at which hydrogen blending (up to 20% vol.) is facilitated, which calls for more decisive policymaking and accelerated action from GDNOs.

Compared to natural gas pipelines, the CAPEX of new hydrogen pipelines may prove 10%–50% more costly [104] (see Table S7). By

[26] Cost improvements are anticipated from higher efficiencies, less degradation, higher availability, larger cell sizes, higher operating pressure, and less critical material use together with overall reduced material use [193].

[27] Whereby experience with a technology drives down the unit cost of production over time [402].

[28] Compared to Saadi et al. [210], DeSantis et al. [194] calculate a lower pressure drop for hydrogen transport relative to natural gas, therefore, the volumetric flow is higher in the hydrogen pipelines.

[29] European Agreement Concerning the International Carriage of Dangerous Goods by Road.

[30] 3 kWh/m^3 compared to 10 kWh/m^3 for methane.

[31] However, hydrogen has a higher flow rate than natural gas which may help drive down unit costs through economies of scale [158],

[32] Since hydrogen has a faster flow rate than methane, the pipeline capacity required per unit of energy is only ~20% more [103].

[33] The IMRRP implements a three-tier approach. In Tier 1, 80% of all 'at risk' iron pipes (8 in. or below) are upgraded with PE. The programme is set to conclude by the end of 2032 [213,403].

[34] Project Union aims to decarbonize large clusters of industry, connect to hydrogen storage locations, integrate increasing volumes of electrolytic hydrogen, and could create cross-border markets for low-carbon hydrogen [104,121].

contrast, European transmission system operators (TSOs) estimate that repurposing existing pipelines may prove 10%–25% less costly than building new hydrogen pipelines [104]. Reflecting the lower CAPEX associated with repurposing infrastructure [90,104,216],[35] the European Hydrogen Backbone (EHB)[36] envisions 75% retrofitted pipelines [104].[37] Ultimately, decisions around pipeline construction must be made on a case-by-case basis with involvement from TSOs, GDNOs, and end-users.

4.1.3. Hydrogen storage

Hydrogen storage may prove equally important to production when considering the feasibility of the hydrogen economy. Foremost, large-scale storage is needed to strengthen the flexibility and resilience of the energy system, which can help reduce costs [29]. However, "reliable, safe, effective, and efficient" storage solutions are yet to be established [217]. At the outset, there are significant cost barriers to overcome, given that storage may contribute 24%–35% of CAPEX for a blue hydrogen production plant [177].

CGH_2 can be stored in containers above ground, but higher pressure is needed to contain the equivalent amount of stored energy [103]. Compared to CH_4, storing compressed hydrogen is at least 50% more costly due to its lower volumetric density [96]. Due to operating costs and material properties, large-scale storage of CGH_2 is typically limited to pressures below 100 bar in aboveground vessels and below 200 bar in geological formations [218] (see Table S8). Overall, underground hydrogen storage (UHS) requires significantly less investment costs than large-scale hydrogen storage above ground [219]. Alternatively, liquid organic hydrogen carriers (LOHCs)[38] – relying on hydrogenation and subsequent dehydrogenation of organic molecules – could offer a viable solution for safe and efficient hydrogen storage, alongside more conventional use for transportation purposes [220].[39] Additionally, the potential for flexible linepack storage (i.e. the inherent storage capacity within the gas grid) needs to be carefully considered in energy transition models [155,196].

4.1.3.1. Underground hydrogen storage. Each UHS method entails its own distinct characteristics [31], calling for case-by-case analysis of the geological integrity and techno-economic parameters of each storage site [216]. Although the entire seasonal demand for UK residential heating could potentially be balanced via hydrogen storage in just a few offshore gas fields [33,221], this option presents problems of chemical reactions and environmental pollution, as evidenced by the historic storage of town gas [222]. BEIS concluded that depleted hydrocarbon fields are unsuitable for hydrogen storage due to residual contaminants, such as sulphur compounds [223]. Hydrogen storage in depleted hydrocarbon fields may also result in an unpredictable blend of hythane (methane and hydrogen) [103]. Similarly, in deep seated aquifers, undesirable reactions may produce gases such as H_2S and CH_4 with loss of hydrogen [31], while gas leakage is unavoidable [222]. Notwithstanding, research into the feasibility of these storage options remains nascent [29].

Where geologically viable, salt caverns – artificial cavities built in salt deposits [224] – may provide a preferred option for UHS due to several advantages (see Table S9), including low construction costs, fast withdrawal and injection rates, low leakage rates, minimal risks of hydrogen contamination, and relatively low cushion gas requirements [219,224,225]. Based on the UK and US experience since the 1970s, salt caverns have proved a technically feasible method for achieving large-scale hydrogen storage [31].[40] Notwithstanding, due to the geographic scarcity of salt caverns in the UK [223], transporting this energy to consumers in important demand centers such as London and the Southeast would incur high costs and significant logistical barriers [29].

4.1.3.2. Cost factors for underground hydrogen storage. The cost of UHS consists of construction, operating, maintenance, and decommissioning costs [219,224]. UHS in salt caverns or depleted hydrocarbon fields present more predictable cost estimates than in aquifers, while the costs of the former are expected to be less [224]. Salt caverns offer an economical way to store hydrogen, reducing costs to less than 1% of electricity storage in batteries [193] and allowing for intra-day, daily, weekly, or seasonal operation [223]. The key costs of hydrogen storage in salt caverns include CAPEX for construction by dissolution, and the cost of the gas cushion for maintaining minimum storage pressure [31]. Additionally, the length of the pipeline used to discard the brine is an important cost factor, especially when suitable disposal sites are located far offshore [31,224]. Counteracting these cost barriers, larger cavern size and more favorable geological characteristics may improve economies of scale [31]. Overall, the CAPEX and OPEX of salt caverns are higher than for depleted hydrocarbon fields, but less than in aquifers [31]. However, the costs of salt cavern storage are projected to decrease by one-third [96].

4.1.3.3. Barriers to underground hydrogen storage. Challenges and uncertainties facing UHS remain extensive, as documented in a recent review by Tarkowski and Uliasz-Misiak [226] which identified 25 unique barriers, ranging from geological and reservoir constraints, and technical and safety limitations, to legislation and regulations, potential conflicts of interest, and social acceptance. On the technical side, the unique properties of gaseous hydrogen such as "its high penetrability and negative influence" on steel present barriers to safe UHS [31]. The cost of the borehole injection/withdrawal with its required tubing is much higher than for CH_4, given the need for materials that are impermeable for hydrogen and resistant to embrittlement [31,227]. The behavioral properties of hydrogen may also present additional complexity compared to natural gas when it comes to underground storage [31].

Mathematical modeling has demonstrated that UHS generates CH_4 emissions by behaving like a natural chemical reactor [228], whereby hydrogen acts as "a universal electron donor" for the metabolic activity of different hydrogenotrophic species (e.g. methanogenic archaea, acetogenic archaea, sulfate-reducing bacteria, and iron-reducing bacteria) [229]. Specifically, Hemme and van Berk [230] showed that the generation of hydrogen sulfide (H_2S) and related contaminants by bacterial sulfate reduction presents a risk in salt caverns. Given the co-existence of different microbial species, there is likely to be more competition [229] and resultant loss of hydrogen [31]. In salt caverns, there may be additional risk of impurities in withdrawn gas caused by undesirable reactions between hydrogen and interbeddings other than salt, alongside other limitations (see Table S10). Notwithstanding, evidence on the impacts of subsurface microbial communities and other risks remains limited [155].

Overall, using salt caverns to store hydrogen is not dissimilar to natural gas, in respect to the main risk associated with geological

[35] The levelized cost of transmission (LCOT) for hydrogen is estimated at €3.7/MWh_{H2}/600 km for repurposed natural gas infrastructure, compared to €4.6–11.4/MWh_{H2}/600 km for new hydrogen-dedicated infrastructure Calculations used in these estimates are for the Euro in 2019 [404].

[36] Potentially scaling up from 6800 km in 2030, to 23,000–30,000 km of pipelines by 2040 [104,405].

[37] With diameters ranging between 24 and 48 in., providing 3–13 GW (LHV) transport capacity per pipeline [104].

[38] LOHCs account for all hydrogen storage systems that are liquid in their hydrogen-rich form and can undertake this reversible chemical reaction [181].

[39] See Yang et al. [406] for a recent review of hydrogen storage options.

[40] For example, 1 million m^3 of pure hydrogen (95% H_2 and 3%–4% CO_2) is safely stored at three salt caverns located in Teesside in North East of England, serving as a local industrial feedstock for the production of ammonia and methanol [31].

uncertainty [224]. However, it should be noted that the socio-political acceptance of UHS remains largely unattested [29,226,231], therefore assumptions should not be made that past experience with gas storage will be directly transferable to hydrogen. For example, evidence from Germany highlights public concern over safety and security issues [231], which suggests that gaining a social licence to operate (SLO) hydrogen (and CCS) may prove problematic [232,233]. Even within a favorable socio-political environment, moving from theoretical estimations of UHS to actual site-specific development will require lengthy permitting and planning procedures, which may restrict prospects for cavern development in certain areas and within a net-zero timeframe [29].

4.1.4. Visualizing techno-economic barriers to the domestic hydrogen transition

Techno-economic barriers to the DHT are extensive and cut across all parts of the hydrogen supply chain (see Fig. 8). A multipronged approach is imperative to tackling a range of challenges and issues around energy resources and security of supply, the volatility of gas and electricity markets; alongside the scaling up of low-carbon hydrogen production, transport, distribution, and storage, together with CCS. Each of these components of the HES must be safe and economic. Having dissected the main techno-economic factors shaping the hydrogen economy, the next section discusses technical factors concerning hydrogen safety and appliance performance.

4.2. Technical factors

Technical risks and safety issues impact all areas of the hydrogen economy [55,234]. Potential technical barriers revolve around the inherent hazards and risks of hydrogen fuel, as well as specific issues concerning pipeline integrity, appliance performance, monitoring and metering requirements, and emissions and pollutants. Given that hydrogen has a high sensitivity to detonation [60], risks include potential damage to property such as industrial facilities and hydrogen vehicles, as well threats to health and safety, and the environment [209,235,236].

Despite its risk profile, hydrogen has been used safely across a range of applications [4,60] including aerospace [237,238], petrochemicals [239,240], and electronics [241]. There is a scientific consensus that hydrogen presents no significant additional risks compared to other liquid or gaseous fuels in terms of storage and consumption [60]. Nevertheless, using hydrogen in residential and commercial applications is likely to raise additional concerns [116]. Compared to industrial applications, adherence to safety measures is significantly harder to enforce and monitor [242], for example, in the case of hydrogen fueling stations (HFSs) or HFCVs [243–245] and moreover, in residential applications [22].

4.2.1. Hydrogen detection and monitoring

Despite technical advancements, there is still uncertainty over whether national gas grids, such as the UK's National Transmission System (NTS) and Local Transmission System (LTS), will be compatible for transporting and distributing 100% hydrogen [111,167]. In parallel to testing the compatibility of the gas grid, robust detection and monitoring strategies are needed to minimize the risk of hydrogen leakage [246]. Due to its small molecular weight, hydrogen has a high tendency to leak through pipelines and storage containers [18,247], leaking at a rate of 1.3–2.8 higher than that of gaseous methane and four times that of air [4]. Hydrogen exhibits high diffusivity through a range of materials and is four times as diffusive as CH_4 [247]; calling for constant and accurate monitoring of leaks throughout transport, storage, and use [247]. In typical polymer pipes, permeation rates for hydrogen are about 4 to 5 times faster than for CH_4 [248]. Although hydrogen is not considered toxic in nature, when it releases in confined spaces, there is still a risk of asphyxiation since it can reduce oxygen concentration below 19.5% by volume [18].

4.2.2. Technical risks of hydrogen blending and domestic hydrogen

Investigations into hydrogen blending, whereby small quantities of hydrogen are injected into the existing natural gas grid [21], date back to the 1980s [249]. Notably, the NATURALHY-project (2004–2009) examined the conditions under which pure hydrogen blending could be safely used in natural gas pipelines [250,251]. The project demonstrated minimal impacts on straight pipelines with blends up to 25% [252]. Other estimates are more conservative, suggesting that a hydrogen blend of about 10% has negligible impacts on existing pipelines and appliances [253]. Although a promising steppingstone to the wider transition [43], injecting hydrogen into natural gas networks will present technical and safety challenges [22,116].

Hydrogen has a higher flame speed [107] and adiabatic flame temperature than CH_4 [254,255], which increases the potential for explosive risks [7,256]. As a result, there are additional challenges for handling and storing hydrogen safely [60]. Additionally, hydrogen has a wide flammability range (4.0–75 *v*/v%) in oxygen [90,109] compared to CH_4 (5–15.6 v/v%) [257], with explosive mixtures occurring between

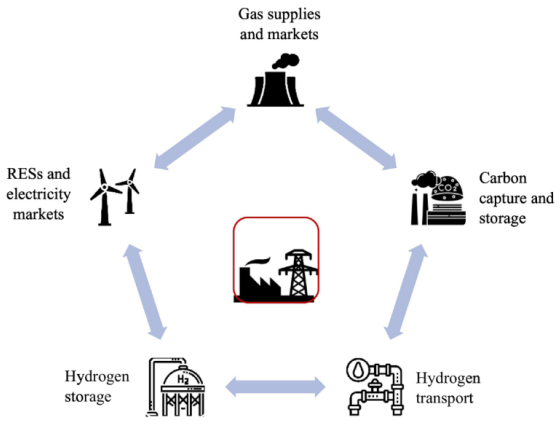

Fig. 8. Interactions between key techno-economic barriers.

concentrations of 18–59 v/v% [18]. These flammability characteristics [9],[109][41] may decrease the lifetime durability of hydrogen appliances, while increasing the need for more frequent and modified maintenance measures [112]. Relatedly, flame flashback – a function of flame speed – is significantly higher for hydrogen compared to CH_4 [110,196]. As the flame burns closer to the gas ring or oven burner [109], the risk of hydrogen flashback increases, which can result in damage to the burner and lead to appliance shutdown [105]. Without prevention from a hydrogen flame arrestor [61], flashback can cause an explosion hazard if the combustible mixture spills over [110]. Critically, de Vries and Levinsky [259] observed that minimizing the risk of flashback and other safety issues concerning hydrogen would require a reduction in the thermal performance of domestic appliances.

Based on experimental tests on a representative natural gas cooktop burner, intermittent flashback occurs when 20% hydrogen is blended with natural gas [109]. Although the overall combustion performance of appliances may not be significantly affected by an addition of about 15% hydrogen [109], it is recommended that the maximum blend should not exceed 15%–20% to prevent downgrading natural gas quality [62]. Zhao et al. [109] concluded that it is feasible to use hydrogen on existing cooking appliances within these limits without the need for technical modifications, while also observing that hydrogen blending reduces pollutant emissions. However, Dorrington et al. [112] highlighted an additional barrier concerning the configuration of new flame retention ports, which act to prevent the flame from lifting off the burner. The authors concluded that converting dual fuel cooking appliances presents a greater technical challenge than boiler conversion, especially given the nature of damage and spoil to cooking apparatus from extensive food spillage [112].

Given that the volumetric density of hydrogen (0.0899 kg/m^3 [247]) is almost three times lower than CH_4 [252],[42] compression energy will be approximately three times greater for hydrogen transmission with the same pressure drop [252]. Consequently, blending hydrogen into the existing pipeline will lead to a significant decrease in mass flow rate, resulting in less transmitted energy [66].[43] Hydrogen blending could also prove technically challenging since different measuring instruments, control stations, and compressors will be required [65]. This includes smaller gas meters to accommodate hydrogen's volumetric flow rate and different valves to prevent excess flow [112], as well as changes to consumer billing (see Section 4.4.3). For example, the GRHYD demonstration project in France [260] found that the presence of 20%vol. hydrogen in gas would cause a metering difference up to 2.5% [252].

In the short-term, blending hydrogen into existing gas networks may provide a viable opportunity to rapidly scale-up hydrogen supply at lower capital expenditure (CAPEX) [103,261]. Evidence suggests that blending percentages of at least 5% and up to 20% hydrogen should be technically feasible with minimal investments [101,103,108]. Notwithstanding, blend concentration, even at fractions of 5%–15%, must be assessed on a case-by-case basis to account for specific end-user typology and variation of natural gas composition within pipelines [123,252,262]. Moreover, moving to higher blending percentages will call for changes to infrastructure and equipment such as different burners [103]. This will increase environmental risks, technical challenges [263,264], and potential costs [123,262]. Notably, regarding emissions, Colorado et al. [263] found that a mixture of natural gas with up to 70% hydrogen promotes the formation of nitrous oxide (N_2O), which is a trend not observed with other gaseous fuel mixtures such as biogas.

4.2.3. Visualizing technical barriers to the domestic hydrogen transition

Despite sustained research efforts and growing technical understanding, a knowledge gap remains regarding the safe transport and use of hydrogen or methane-hydrogen mixtures [116], with scientific knowledge on the risks of domestic hydrogen remaining low in comparison to CH_4 [265]. Clearly, barriers to securing technical feasibility, such as hazards and risks, pipeline integrity, appliance performance and safety will need to be addressed if hydrogen home appliances are to penetrate the UK market at a meaningful scale (see Fig. 9). As a starting point, more experimental studies are needed to bridge the gap between safety levels for hydrogen and hydrocarbon technologies mixtures [116], including research regarding the technical feasibility of hydrogen blends above 20% [266]. Having reviewed the technical aspects of the DHT, the next section introduces the soft side of the transition through a review of political factors [147].

4.3. Political factors

Regulatory engagement is needed across the hydrogen value chain; from safe production, storage, and transportation, to market incentives and business models [118,121] (see Table 3). Critically, regulators should address the lack of harmonization regarding codes and standards for the transport and transmission of hydrogen [118]. For example, the lack of a harmonized policy and regulatory framework between the European Union (EU) and UK impedes ambitions to be reap economic benefits as first movers in the global hydrogen economy [30,267,268]. Notably, there are significant disparities between national thresholds for hydrogen blending, owing to a range of legacy codes and standards [98,118,269,270]. Compounding this issue further, there is still no scientific consensus about safe thresholds limits for hydrogen blending [271].

Thus, identifying 'legal pathways' [272] and implementing adequate policy mechanisms is crucial to enabling transparent procedures for national hydrogen plans, especially renewable-based projects [271]. Establishing international agreements around low-carbon hydrogen standards, as well as future cross-border trade [1], can help support best practices for hydrogen safety, while also accelerating cost reductions for producers and consumers through learning-by-doing and a more liquid global market [96].

4.3.1. Visualizing political barriers to the domestic hydrogen transition

Multiple political barriers inhibit the scaling up of HESs, with most countries yet to develop legal frameworks to support national hydrogen economies [270]. These barriers revolve around the development of international agreements, regulatory frameworks, legal and administrative procedures, codes and standards, and land-use planning procedures (especially for green hydrogen projects) (see Fig. 10). Overcoming deployment barriers to the UK hydrogen economy and the DHT – whether technical, commercial, regulatory, or societal – will require sustained political will. The next section addressed the commercial side of the transition through a review of market factors.

4.4. Market factors

The diffusion of hydrogen appliances will depend on TRL, market penetration, and subsequent market growth [158], which can also be examined in terms of barriers to market entry, development, and support [112]. Overcoming barriers to each stage of the technology curve will hinge on interactions with other socio-technical factors, [273,274] (see Table 4). At present, the global hydrogen supply chain is still in its infancy and faces significant challenges to scale up [57,164,223].

[41] Hydrogen's laminar burning, buoyant, and propagation velocities exceed that of other fuels, while its vapor-from-liquid-generation-speed is higher than fossil based liquid or liquefied fuel [60].

[42] Approximately 3.6 kWh/Nm3 or 12.8 MJ/Nm3 for hydrogen, compared to 11.8 kWh/Nm3 or 42.3 MJ/Nm3 for natural gas [252].

[43] Overall, hydrogen injection increases the upper and lower flammability limits and compressibility factor, whereas both lower and higher heating values, lower and higher Wobbe indices, along with the relative density, decrease [90].

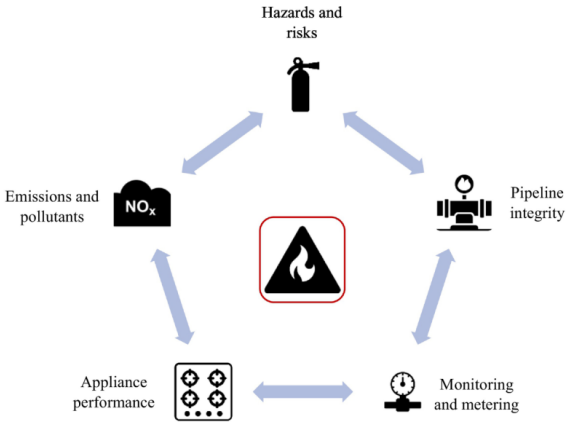

Fig. 9. Interactions between key technical barriers.

Notably, unlike other energy sources and commodities which are publicly traded, hydrogen is currently traded via bilateral agreements between companies [98]. This limitation is reflected by the global hydrogen generation market being valued at about 3% of the global oil and gas market in 2020 [275,276]. The rest of section discusses these market barriers in more detail.

4.4.1. Supply chain barriers

The Scottish government has reported underlying deficiencies in areas of design, manufacture, and maintenance for production, storage, and transport of hydrogen, which calls for new skills and training in the workforce [198]. Irrespective of the specific hydrogen production pathway, a greater number of Chartered Engineers and qualified technicians would be needed to deploy hydrogen homes at a large-scale [111], as experienced with the national transition from town gas to natural gas [277,278]. It is anticipated that the UK will face regional constraints for skilled labor when pursuing a transition to domestic hydrogen appliances [223].

In addition to labor constraints, the costs of research and development (R&D), product design, and initial manufacturing for hydrogen appliances will exceed the costs of natural gas appliances [112]. Even when suitable production facilities are in place, bottlenecks are likely to arise when components and materials used in natural gas appliances cannot be transferred to hydrogen appliances,[44] especially if UK manufacturers become reliant on their European counterparts for specific components, such as gas valves, seals, controls, and burners [112]. Walker et al. [223] further highlight that the build rates for several components will depend on unpredictable global supply chains. The green hydrogen supply chain faces similar risks, given that only two electrolyzer factories are currently operational in the UK, both of which are in England [121]. A related barrier concerns "the intertemporal integration" between a prospective hydrogen supply chain and existing supply chains, which is yet to be examined in detail [164].

4.4.2. Informational barriers

There is an information gap concerning the market demands (e.g. gas quality, appliance outputs, thermal efficiency and NO_X requirements) for hydrogen appliances [112], which is compounded by the need to adjust manufacturing warranties [123]. Alongside changes to the permissible concentration of hydrogen in the gas network, manufacturing warranties – associated with plant machinery and equipment, and domestic appliances – would also need to be adjusted to support market entry and development [123]. It follows that the appliance industry needs more information about the market requirements for hydrogen products to meet the expectations of both policymakers and consumers [112]. In parallel, leading boiler manufacturers will need to align their goals [279] to compete with low-carbon alternatives such as heat pumps. Alignment between manufacturers is important for promoting brand loyalty and consumer buy-in for hydrogen appliances.

4.4.3. Barriers to consumer billing

At present, gas consumption is billed according to an assumed energy content which is held uniform across the gas network [123]. However, should hydrogen be injected into selective regions of the UK, the energy content of mains gas would in turn vary by location [123]. Hydrogen has a lower volumetric calorific value (CV) than natural gas, therefore, gas meters would register a higher volume of use for the same energy input, which would expose consumers to potentially variable and overpriced charges [123]. In response, new methods are required to determine energy content at all points of the gas network [252]. Addressing this challenge would call for a rethink from the Office of gas and electricity markets (Ofgem) about how to bill consumers for gas use [123].

Cadent Gas Ltd., the UK's largest GDNO, has developed the Future Billing Methodology (FMB) project to develop solutions that will enable lower-CV gases such as hydrogen to be embodied accurately into consumer billing. The expectation is that a modification would be required to the uniform network codes (UNC) [123], which govern commercial transactions between gas shippers, transporters, and suppliers. To carry out the hydrogen conversion, hydrogen sensors and new meters would need to be fitted to each home to enable householders to be billed according to CV of gas consumption [214].[45] As supply-side mechanisms develop, market factors will prove critical to determining what tariffs, business models, and other conditions prove acceptable to different consumers.

[44] This may include high temperature seals and gaskets, sizing of various components, and pressure regulators [112].

[45] Based on the UK MARKAL energy systems model (calibrated to UK energy consumption in 2000), this could an additional cost of £230 to £490 per house [214].

Table 3
Impacts of policy barriers to hydrogen development and deployment.

Identified barrier	Implications for hydrogen development and deployment
Regulatory framework for the international transmission of hydrogen (maritime, pipelines) still not harmonized	• Hinders international trade of hydrogen
Emissions reduction schemes and internationally agreed framework for pricing carbon emissions not in place	• Hinders the development of a renewable hydrogen market • Hinders international trade of hydrogen • Hydrogen use remains economically unattractive across multiple use cases
Certification schemes such as Guarantee of Origin (GoO) for renewable hydrogen are still in development	• Hinders the development of a renewable hydrogen market • Constrains the overall environmental benefits of hydrogen across the energy system • Hinders international trade of hydrogen
No common definition of 'green'/ renewable hydrogen in regulatory and policy frameworks	• Divergent national approaches jeopardize the movement of green hydrogen across borders, • Acts as a barrier to the implementation of renewable hydrogen projects • Increases uncertainties associated with production pathways and certification schemes, which may restrict investments
Lack of a 'simplified process' for low volume hydrogen production and storage,[a] as this remains relative to the site and site specific/operational safety risks	• Prevents the easing or removal of some aspects of regulation, compliance, and permitting related to Hazardous Substances, and Control of Major Accident Hazards (COMAH)[b]
Current legal and administrative procedures, including land use planning and associated zoning limitations or exclusions, do not generally distinguish between hydrogen production methods	• Limits the ability for planning authorities to leverage and potentially incentivize production of hydrogen through relatively safe, low environmental impact methods such as electrolysis • Large-scale industrial producers (i.e. SMR-based) and smaller-scale producers using electrolysis face similar planning restrictions, which may discourage investment in local, distributed hydrogen production
Lack of a formal, clear, and coherent payment framework in place across between regions (e.g. UK and EU) for hydrogen transmission; covering connection fees and charges, or covering renumeration for hydrogen supplied/injected	• Limits the business case for hydrogen systems • Delays projects from passing beyond the demonstration phase
Tariffs apply to electricity consumed for hydrogen production	• Increases the relative price of electrolytic hydrogen compared to other hydrogen production mechanisms

Source: Compiled from [26,96,118,123].
[a] Considered as chemical storage of flammable and dangerous (industrial) gases from a legal and administrative perspective.
[b] Hydrogen storage may fall under Hazardous Substance regime at 2 t or under the COMAH Directive at 5 t.

4.4.4. Visualizing market barriers to the domestic hydrogen transition

Early progress has been made on addressing some of the existing market barriers, through innovations such as the FBM, while the boiler industry's 'Big Four' (Worcester Bosch, Vaillant, Baxi, and Idea) have made a price promise on hydrogen-ready boilers [279]. However, overcoming barriers to market entry and development will require increased R&D to increase the TRL of different hydrogen technologies, alongside a massive ramping of the domestic supply chain and a diminishing informational barriers, to enable viable business models for hydrogen home appliances (see Fig. 11).

At the national level, the fragmented structure of the UK gas market [37] – composed of "producers and exporters of gas as a commodity; suppliers and traders of wholesale and retail gas; generation, regasification, and storage asset owners; and network owners and operators" – may also impede coordination across the supply and value chain, should respective actor groups present conflicting motivations and priorities [123]. In addition to the current gas network being much more interconnected and vulnerable to supply disruptions than during the conversion from town gas, the privatized nature of the current gas network presents more of a logistical and financial barrier than during the era of centralization [214].[46] Completing the socio-technical transition framework for the DHT, the next section discusses social factors, which span ethical, environmental, safety, economic, and socio-cultural aspects.

4.5. Social factors

Mixed methods studies on public perceptions of domestic hydrogen [21–23] indicate that social acceptance may rest on consumer attitudes towards equity and fairness, the environment, safety, cost factors, and behavioral impacts. However, existing perceptions of hydrogen technologies may be rooted in misconceptions due to an underlying lack of knowledge and awareness across society [115,243,280]. Against this backdrop, this section provides an overview of prospective barriers to hydrogen acceptance.

4.5.1. Public perceptions of equity and fairness

To date, a limited number of studies have engaged with issues of equity and fairness linked to the DHT. In the UK context, questions of energy justice [281,282] are especially pertinent given the spatial dynamics of the housing stock, where approximately four million households (~15%) are without connection to the gas grid [283]. From an energy equity perspective, these households – typically living in hard-to-treat, off-grid areas [100] – could be doubly excluded from the energy transition if denied access to hydrogen networks or electrification [67]. Both location and housing type present a challenge to achieving energy equity [67] (see Table S11). Furthermore, the UK hydrogen economy is developing in proximity to major industrial zones [284]. Such areas of the country are strongly characterized by disparate economic and social geographies [21], alongside a higher prevalence for fuel poverty [285,21]. This reality exacerbates the challenge of achieving a fair and efficient decarbonization pathway for the residential sector.

4.5.2. Public perceptions of environmental impacts

Public perceptions of environmental impacts have been shown to influence the social acceptance of new energy technologies [286,287]. Whether these perceptions are established on grounds of knowledge and awareness [288,289], or more rooted in culture [290], both the early [291–293] and more recent literature [21,23,294] supports the notion that environmental views are likely to shape hydrogen acceptance. Overall, the literature is quite emphatic on a consumer preference for renewable hydrogen, at least in the long-term [21,295,296]; inferring that non-renewable-based production methods may spark social resistance or opposition, especially across socio-demographic groups that are more culturally, psychologically, or emotionally engaged with environmental issues [23,75,296]. Notwithstanding, the UK public acknowledges an underlying level of uncertainty regarding the timeframes involved in developing infrastructure to produce renewable hydrogen at scale [297].

4.5.3. Public perceptions of cost factors

Evidence suggests that the UK public may perceive the economic impacts of hydrogen at the national or macro-level to be positive or at least neutral [21]. In contrast, at the household or micro-level, cost

[46] British Gas was privatized in 1986 under the Thatcher government [407].

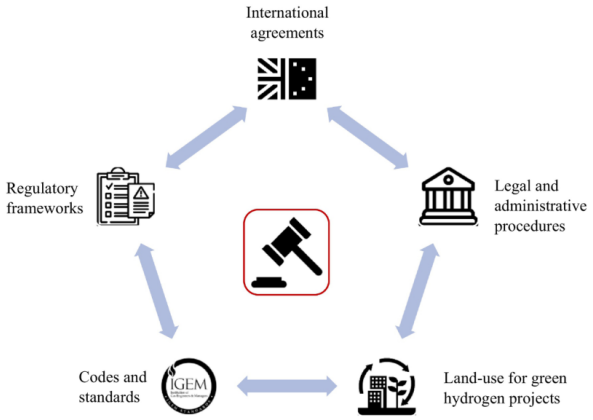

Fig. 10. Interactions between key political barriers.

Table 4
Market barriers identified by UK manufacturers and trade bodies.

Market barrier types	Identified barriers
Market entry	• Lack of necessary codes and standards for hydrogen boilers • Absence of a hydrogen quality standard • Insufficient number of trials and demonstration projects. • Smaller companies and new entrants will need to establish new sales and distribution channels, or cooperate with larger companies with established sales relationships • Lack of consumer awareness regarding the benefits of hydrogen • Lack of confidence in the safe operation of hydrogen appliances
Market development	• Lack of demand for hydrogen appliances • Lack of business models to support hydrogen appliances being sold in volume • Bottlenecks due to deficient engineering capacity • Lack of clear policies incentivising R&D resources to the manufacturing of hydrogen appliances • Limited number of appliance manufacturers, specific product designs, and commercially available products • Competition for R&D capacity and skilled labour
Market support	• Where technical solutions exist, there is no market pull to create supply chains • Financing mechanisms for converting appliances need to be established to resolve uncertainties • Specific training requirements for engineers/installers to install and repair hydrogen appliances

Source: Compiled from Dorrington et al. [112].

factors (i.e. purchasing, running, and potential maintenance costs) present the main barrier to securing consumer support [21,298]. BEIS reported that consumers are highly concerned about the investment, operational, and lifetime costs of hydrogen appliances, with strong interest in how the switchover may impact energy prices and tariff structure [169]. Based on related survey studies conducted in the North of England [22,298], delivering cost-competitive running costs may have a more pronounced impact on social acceptance. In this region of the UK, the affordability challenge looms large, since a combination of high energy bills and low wages have already led to a propensity for fuel poverty [21,22]. In response, there is a strong expectation that government subsidies and financial schemes will be available to encourage technology adoption, which the public expect to be subsidized [295,297]. Beyond these findings, there is limited data on the public's willingness to pay for domestic hydrogen, which presents a significant barrier to developing a comprehensive hydrogen strategy.

4.5.4. *Public perceptions of hydrogen safety*

As described in Section 4.2, hydrogen has distinct physical and chemical properties which may raise public concerns over safety risks, especially when improperly explained or misunderstood [299]. While most safety-related issues are attributed to hydrogen's volatility and flammability [23,74,299], the production context may also influence safety perceptions [21,22]. For example, in the case of green hydrogen, the Welsh public expressed concerns over explosive risks, which were heightened due to hydrogen's unfamiliarity compared to natural gas [299]. Interestingly, some consumers may be more worried about the safety of CCS for enabling a blue hydrogen pathway [300,301], as opposed to hydrogen-specific risk factors.

Closing social acceptance barriers around safety may prove more feasible if hydrogen first becomes visible in other areas of energy and infrastructure, such as industry and transport [43]. This could prove especially critical if the public has an expressed preference for using hydrogen in commercial applications, as opposed to residential settings [295]. In the same way that blue hydrogen may be viewed as an enabler of green hydrogen [30,302], developing other sectors of the national hydrogen economy may strengthen hydrogen's social standing [303] in the residential context.

4.5.5. *Public perceptions of behavioral impacts*

Given that very few consumers have seen hydrogen appliances first-hand, let alone tested them at demonstration facilities such as Spadeadam [304], there is scarce data available on potential behavioral impacts. To date, hypothetical studies highlight that consumers value preserving the lived experience of gas heating and cooking, which will require hydrogen appliances to deliver across the board in terms of functionality, appearance, maintenance requirements [169], safety and security [21,22]. Evidence suggests that consumer acceptance would be encouraged if hydrogen boilers can provide a close substitute for gas boilers by providing an efficient, quiet, and minimally disruptive heating system, which has limited impact on domestic energy practices [37,305,306]. However, given the intimate nature of domestic kitchen activities, consumers may have stronger reservations about the 'socio-material nature' of hobs than boilers [22]. Whereas boilers are typically as out-of-sight and removed from day-to-day interactions [22], cooking appliances may bring about undesirable changes to incumbent social practices [37].

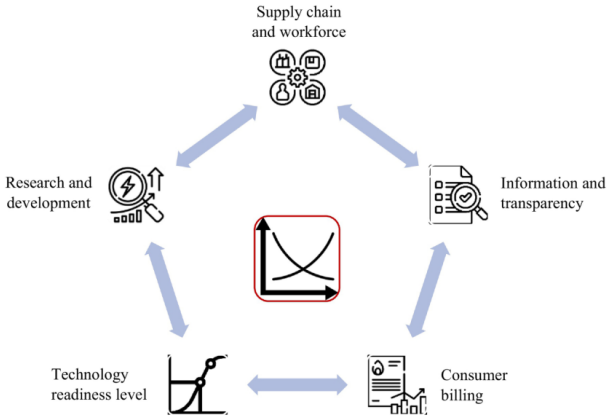

Fig. 11. Interactions between key market barriers.

4.5.6. *Visualizing social barriers to the domestic hydrogen transition*

International research on social barriers to the DHT remains considerably nascent and largely constrained to the UK, European, and Australian context, with several of these studies found within the grey literature [298,307,308]. Notwithstanding, a few articles have recently entered the academic literature [21–23,67], with the available evidence suggesting that social barriers concern the following areas: energy injustice and other social inequities; changes to the lived experience of heating and moreover, cooking; health and safety issues; cost factors; and underlying perceptions of social and environmental impacts (see Fig. 12).

4.6. *Linking socio-technical factors and barriers*

Through identifying the main socio-technical factors impacting shaping the DHT and the broader hydrogen economy, Section 4 enables a more integrated analysis of interactions between different dimensions of the socio-technical system for hydrogen homes. Next, Section 5 explores these interactions in a systematic way by applying the framework to the UK context. In doing so, this analysis advances the discourse around the feasibility of converting natural gas grids to hydrogen [168], accounting for the impacts of both blue and green pathways vis-à-vis the twin track approach [43].

5. Interactions between socio-technical factors: Breaking down barriers to the domestic hydrogen transition

5.1. *Cross-scalar dynamics and policy inadequacies*

The policy environment for supporting HESs is relatively nascent, reflected by a nexus of barriers interacting across different levels of the hydrogen economy. Firstly, policy barriers must be overcome to realize ambitions for aligning mega-projects, such as the UK industrial hydrogen backbone and the EHB, as well as more localized projects. Existing policy mechanisms fail to support strong progress on this front, owing to a lack of codes, standards, or payment frameworks for cross-border transport/transmission. This weakens the prospect of developing international supply chains, which is important for strengthening energy security and international hydrogen trade. Playing out more visibly at the national level, the absence of specific standards for designing or installing hydrogen appliances creates market uncertainty for manufacturers and the wider industry. This deficiency stifles the

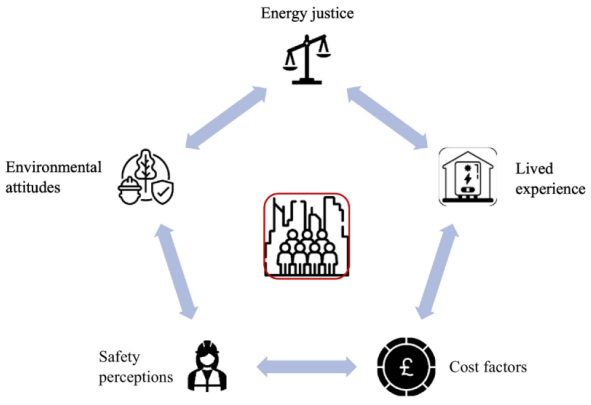

Fig. 12. Interactions between key social barriers.

retraining and upskilling of the UK workforce, which is needed to support a "just transition" pathway [309,310].

The economics of hydrogen production are strongly linked to the costs of electricity and gas, which depends on key technical parameters such as conversion efficiencies [57]. This interaction between "economic viability and technical effectiveness" [311] dictates the feasibility of deploying hydrogen-fueled home appliances in a safe and cost-effective way, which can garner social acceptance at the national, community, and household level. However, one of the preconditions for establishing a functioning market for hydrogen homes lies with developing codes and standards to accommodate higher volumes of hydrogen in UK gas networks [99]. As a starting point, a legal framework is needed to enable the injection of hydrogen into the natural gas grid for distribution and transmission. In the short-term, blending hydrogen at 20% could take advantage of low-hanging fruit for emissions reduction by lowering carbon intensity by up to 7% [99], while helping to mitigate demand risk as the hydrogen economy scales up [167].

A robust national regulatory framework, supported by international agreement around codes and standards, will also help facilitate market development and best practices for hydrogen safety [164]. While negative perceptions of hydrogen's safety credentials appear to be mostly associated with low levels of public awareness and knowledge [22], safety concerns may also permeate the socio-cultural dimension by disrupting the lived experience of heating and cooking [22,169]. Specifically, demography, location, and culture may influence disparities regarding safety perceptions and associated hydrogen acceptance [115]. Coordinated planning and action is required to account for geographic diversities between access to renewable energy resources [312,313] and divergent political dynamics across different parts of the country [314–316]. Otherwise, socio-structural barriers [317] may prove entrenched and challenging to reconcile, as reflected the UK's North-South divide. Thus, availability and access to resources [71], together with institutional factors [26], will carry strong implications for the dynamics of the DHT.

5.2. Dissecting the blue and green of the UK Hydrogen Strategy

While the UK Hydrogen Strategy should be viewed as a major step forward in terms of mapping future pathways and key steppingstones for this decade, some of its momentum and ambition has been curbed by the government's choice to delay strategic decision-making on the role of hydrogen in heating until 2026 [44]. This could potentially offset the scaling-up of demonstration projects [132]. Progress in this area is critical for developing evidence and insights into the regional suitability and feasibility of domestic hydrogen. Trials and demonstrations also lay the foundations for social acceptance [37]. The 2026 decision timeline reduces the likelihood of mandating hydrogen-ready boilers within the next few years [279], which could stall the phasing out of new natural gas boilers by 2035 [43]. Furthermore, policy uncertainty may delay the potential deployment of hydrogen-heat pump hybrids [41,168].

The UK Hydrogen Strategy [43] highlights the degree to which the viability of the DHT rests on parallel, if not significantly faster progress on industrial decarbonization via hydrogen [26], as well as transport and power. Foremost, the nature of these cross-sector dynamics means that the feasibility of hydrogen homes will hang in the balance until tangible progress is made in decarbonizing industrial clusters [232]. Arguably, the very notion of establishing a low-carbon hydrogen economy rests on scaling up blue hydrogen production in the short- to medium-term. However, the blue pathway faces a supply deficit, which could result in greater import dependency for natural gas. If pursued as currently envisioned in the Hydrogen Strategy, this trajectory could expose consumers to commodity price fluctuations and higher energy prices due to increased production costs [318,319]. Currently, parts of the UK population already face a growing fuel poverty crisis [21,285,385], which would be exacerbated if these costs fail to be minimized and socialized equitably.

Doubling down on natural gas via investments in blue hydrogen infrastructure may also prove unpopular with the public on environmental grounds, especially if this route is misunderstood and rejected as a transitional pathway. Arguably, this pathway counteracts the energy transition discourse since it is more emissions-intensive than hydrogen production via wind electrolysis [320], and may lock-in dependence on natural gas for several decades [261]. Notably, the role of blue hydrogen as a transitional fuel and enabler of green hydrogen remains subject to scientific debate, with uncertainties regarding emissions intensity [30,302,321]. Moreover, given that CCS is yet to reach a commercial scale [262], the techno-economic feasibility of blue hydrogen acting as a stimulus for a green hydrogen economy remains unclear. This lack of clarity could derail the foundations for reaching economies of scale for low-carbon hydrogen production.

While the blue hydrogen pathway faces its own set of distinct challenges, existing policy mechanisms designed to support the twin-track approach may diminish prospects for a green pathway. The current playing field for blue and green hydrogen appears unequal, which casts a shadow of doubt over the government's 2030 target for electrolytic hydrogen. The green hydrogen roadmap is less developed than its blue counterpart and faces more pronounced policy barriers, especially given the government's lukewarm stance towards promoting onshore wind projects. While the Ten Point Plan, together with the Hydrogen Strategy, promise to back CCUS alongside a ramping up of renewable energy capacity, conflicting narratives and inconsistent price signals between production pathways may act as a barrier to accelerating a clear, strategic pathway towards establishing a hydrogen economy. This is especially true if "a rhetoric of competition" exists between blue and green hydrogen [322], which could derail the impetus of a twin-track pathway.

As discussion around hydrogen production pathways continue to evolve, the scientific community must commit to a parallel investigation that fleshes out how prospective pathways may impact both environmental and social performance [323]. This is pertinent given that the environmental impacts of hydrogen are only partially understood and remain highly context-dependent [264,324]. Alongside understanding leakage rates [18], accelerated progress is needed in establishing safe NO_x legislation to minimize the risk of undesirable health and environmental impacts [325,326], which could otherwise increase the risk of public backlash and rejection of hydrogen.

5.3. Underground hydrogen storage: From technical feasibility to social acceptability

UHS mirrors many of the challenges faced by CCS [227,327], in terms of socio-technical and socio-spatial barriers [31,328]. The CCS literature demonstrates that these parameters must be addressed to facilitate large-scale implementation [329,330] and social acceptance [331–333]. The safe capture and sequestration of carbon must be proven to avoid the risk of public opposition and costly delays [110,239], further highlighting the importance of "cross sector technology interactions" [334] and community acceptance [335]. Notably, hydrogen remains a significantly less familiar fuel than natural gas for most of the UK public [336]. It follows that inclusive planning and stakeholder engagement will be critical to enabling procedural justice [337], which will require careful consideration of the role of CCS [337].

Prospects for developing full-scale hydrogen storage using salt caverns will depend on further research in at least three key areas: geological surveys during cavern leaching; periodic surveys of changes in the cavern during operation; and detailed characterization of the site storage supported by development of digital modeling [31]. As emphasized by Williams et al. [29], "detailed geological, engineering and techno-economic evaluations" are yet to be undertaken. Such measures will help reduce geological uncertainty by improving the knowledge base on specific salt deposits [177], while making the environmental and safety case clearer4 [29,226].

Reflecting the interactions between different branches of the socio-technical system for domestic hydrogen, converting geological space into hydrogen storage will require long-term commitment from both the public and private sector, with coordinated commitment towards intensive R&D activities [31]. To this end, Work Package 4 of the HyStorPor Project (University of Edinburgh) is engaging civil society with UHS to help couple technical feasibility to social acceptability [338].

5.4. De-risking hydrogen supply and demand

Scaling up hydrogen supply and demand across the UK energy system rests with developing "cost-effective network infrastructure" capable of providing security of supply to offtakers and domestic consumers [29]. By seizing the opportunity to use curtailed electricity from offshore wind farms to scale up green hydrogen supplies [198,339], together with a blue hydrogen production base (i.e. SMR + CCS), multiple producers could potentially supply hydrogen to the grid [43]. If diversity of supply is to materialize, a well-defined legal and regulatory regime must first be established for CCS [51]. This is precondition for enabling early commercial projects to reach Final Investment Decision (FID) [261]. By the same token, projects will need to be de-risked to reduce barriers to investment [123,261].[47] In line with the Ten Point Plan, government investment dedicated to de-risking early hydrogen projects could unlock more than £4 billion of private sector co-investment up to 2030 [43]. Given that the costs of manufacturing for hydrogen-fueled appliances will exceed natural gas appliances, regulatory stability is needed to support a new market [43,112]; wherein informational barriers are reduced to enable long-term investment decisions and market confidence for network expansion and repurposing [33].

Overcoming political barriers is also important for accelerating cost reductions for producers and consumers through LBD and a more liquid global market for hydrogen [34]. As highlighted in the case of Scotland (see Section 4.3), regulatory barriers add to production costs which weakens investment risk appetite, while lack of market confidence has negative spillover effects for developing supply chains to meet future demand for appliances. Thus, ensuring sufficient hydrogen demand is imperative to securing sustained policy commitment and market investment for hydrogen infrastructure. Demand for hydrogen appliances rests on both the safety and business case being made effectively, which is contingent on sustained investments in R&D to support a scaling up of demonstration projects [37]. In parallel, targeted information campaigns about the hydrogen switchover should engage local officials, consumers, and other key stakeholders [132]

Regarding the switchover, consumer buy-in may be hindered if appliances rolled-out during the early stages of the transition have shorter lifespans than existing natural gas or future hydrogen appliances [112]. To counteract this potential market barrier, technical advancements must satisfy consumer expectations. This applies equally to the prospect of hydrogen sensors and new meters [37], which present both a financial cost and social risk. Notably, the UK smart meter roll-out has faced ongoing consumer concerns over operability, reliability, trust, privacy, and data security [340,341], which may set a precedent for the hydrogen switchover. In turn, lessons must be learned to demonstrate that the government has a coordinated, whole-systems approach for residential decarbonization, thereby preempting a scenario in which new metering requirements may otherwise provoke consumer resistance [342,343].

The potential for public backlash looms large in the UK context due to past policy failures for various green technologies [344],[301]. To bolster public support in the early stages of the transition, blending trials and early deployment could be strategically targeted at viable hydrogen communities where there is a prevalence of households with old boiler units approaching replacement age (i.e. more than a decade old). This roll-out pathway would have an important co-benefit in tackling fuel poverty and inequality [345], which is paramount to strengthening socio-political acceptance via distributional justice [346].

5.5. Questioning the role of cooking in a hydrogen home

The notion of a hydrogen home and the current trajectory of the DHT aligns to the prospect of decarbonizing both residential heating and cooking [22,63]. However, hydrogen cooking appliances may present a more significant socio-technical challenge, especially in terms of safety and disruption [22]. Behavioral factors are more likely to pose a significant barrier to market uptake, should the lived experience of hydrogen homes fail to be understood in its totality. Given that compartmentalized transitions will have impacts across the hydrogen socio-technical system and supply chain [26], it remains unclear how a potential divergence between decarbonization pathways for heating and cooking may impact the feasibility and potential speed of the DHT. It should also be noted that domestic cooking is significantly less emissions intensive than residential heating [347], which may see the vision for domestic hydrogen isolated to just low-carbon heating. This is tenable given the lack of focus on cooking in the UK Hydrogen Strategy [43] and the scope of electric alternatives [348] such as induction hobs [349,350], which are currently taking an increased market share due to energy efficiency and safety benefits [350].

5.6. Diminishing socio-technical barriers through stakeholder symbiosis

Developing safe and efficient hydrogen production clusters, in sync with appliances for heating and cooking, necessitates a collaborative effort from government, industry, business, and other key stakeholders [37]. The potential for a national hydrogen economy will be strengthened if such actors can quickly coalesce around a shared set of aims and objectives to confront the socio-technical barriers outlined in this study. Internalizing and actualizing this approach are paramount to ensuring that the hydrogen transition can yield its potential net economic, social, and environmental benefits, while preserving fairness, equity, and safety throughout the process. Optimally, 'multi-regime interactions' [141,351], between the gas industry and the renewable energy sector could facilitate synergistic benefits through symbiosis, as both sides come to reap the mutual benefits of a national hydrogen economy. For such synergies to be realized, multiple barriers will need to be strategically and holistically addressed across the hydrogen supply chain.

In addition to diminishing techno-economic, technical, and market barriers, hydrogen acceptance calls for positive alignment between political and social factors, especially pertaining to issues of community acceptance. Confronting these barriers through the application of socio-technical systems thinking should translate to internalizing the importance of social acceptance, as it has been shown that consumer attitudes towards safety, the environment, costs, social fairness, and behavioral impacts may underpin the feasibility of the DHT. While it remains challenging to reliably forecast and quantify the economic costs of the hydrogen transition [155,206], UK policymakers should nevertheless ground their efforts in strengthening procedural and distributional justice throughout all stages of the transition to help realize 'hydrogen hopes for UK homes' [352].

6. Pathways to domestic hydrogen acceptance

As argued throughout this paper, the socio-technical feasibility of the DHT rests on overcoming multiple policy, techno-economic, technical, market, and social barriers. While all five dimensions are interconnected (see Fig. 7), Fig. 13 provides a clearer visual representation of how different socio-technical factors interact both within and across

[47] De-risking measures may include capital grants, feed-in-tariffs (FITs) and premiums, tax incentives, R&D funding, and loan guarantees [96].

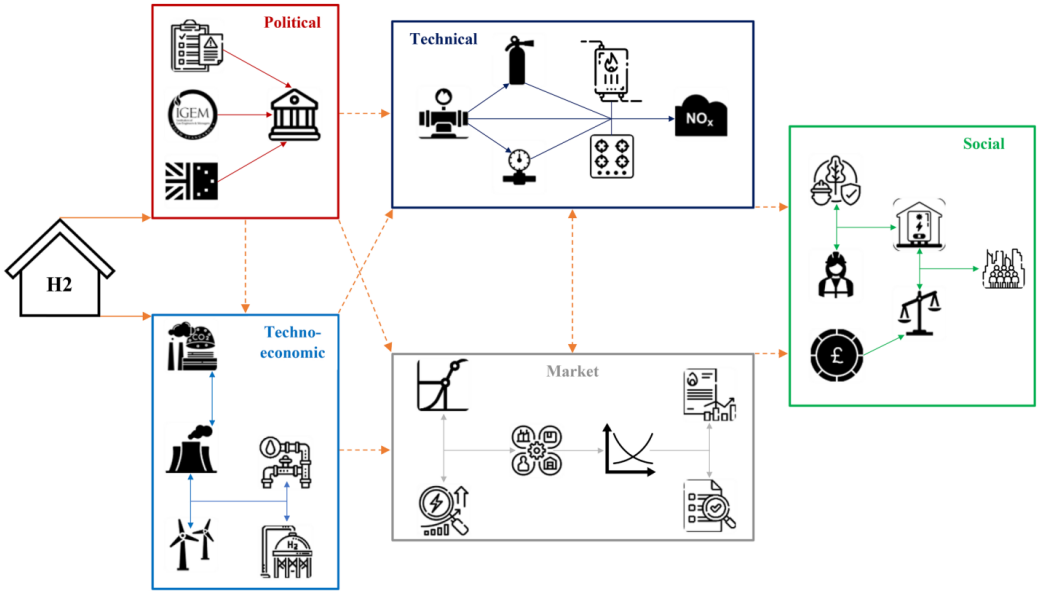

Fig. 13. Interactions between socio-technical dimensions and key factors for enabling domestic hydrogen futures.

Table 5
Key relationships between socio-technical factors within each dimension.

Socio-technical dimension	Summary of observed relationships within dimensions
Techno-economic	• Blue and green hydrogen resources and their respective production costs are interrelated to gas and electricity markets, with blue hydrogen and CCS sharing a direct interaction, which together shape the dynamics of hydrogen transport/transmission and storage (light blue box)
Technical	• The testing of hydrogen blending in existing pipeline infrastructure and optimally, construction of new hydrogen pipelines, advances the deployment of monitoring and metering equipment, and risk assessment practices, which is critical to developing safe, low-carbon hydrogen home appliances (dark blue box)
Political	• Regulatory frameworks based on codes and standards, as well as related international agreements, support legal pathways towards enabling the development of hydrogen projects (red box)
Market	• R&D into hydrogen technologies and parallel development towards higher TRLs support the building of corresponding supply chains and a hydrogen workforce; facilitating the conditions for market demand, as information and price transparency develop, alongside new methods of consumer billing for domestic hydrogen users (grey box)
Social	• Positive environmental and safety perceptions of hydrogen contribute towards behavioral acceptance, while distributional justice and cost factors further shape hydrogen acceptance at the national, community, and moreover, the household level (green box)

Table 6
Summary of interactions between political, market, and social factors.

Political	Market	Social
• A legal and regulatory regime for CCS incentivizes market investment in blue hydrogen projects, and related policy mechanisms (for blue and green hydrogen)	• Help reduce cost barriers and risk for investors • Provides a critical juncture towards building supply chains and a corresponding hydrogen labor force • Enables a consumer market for domestic hydrogen appliances	• Can help support a social acceptance through a just, low-carbon energy transition initiated around industrial towns
• Codes and standards facilitate a legal pathway towards hydrogen blending for short-term emissions reduction	• Hydrogen blending enables the demonstration and early commercial uptake of hydrogen home appliances, including new metering devices	• Can help can offset potential risks of low behavioral acceptance, while supporting social acceptance through positive safety and environmental perceptions

dimensions. Table 5 summarizes the observed relationships between the five dimensions, while Table 6 provides further examples of the interactions between soft barriers to the DHT (i.e. political, market, and social factors).

In the top half of Fig. 13, tackling political barriers (red box) helps overcome technical barriers (blue box), which is needed to enable positive public perceptions of key factors, such as hydrogen safety and environmental impacts (green box). In the bottom half, addressing techno-economic barriers (light blue box) is critical to scaling up the hydrogen supply chain and diminishing other key market barriers (grey box), which together shape important aspects of social acceptance, such as cost-competitiveness and energy justice (green box). Notably, the production costs of blue and green hydrogen will influence wider techno-economic feasibility (transport/transmission and storage), as well as technical feasibility in terms of safety levels, and perceptions thereof, which is a critical determinant of social acceptance.

The dashed orange lines depict the interactions between political,

technical, and social barriers (top half), and techno-economic, market and social barriers (bottom half), in addition to the following four relationships: (1) political factors influence techno-economic factors (red box to light blue box); (2) political factors influence market factors (red box to grey box); (3) techno-economic factors influence technical factors (light blue box to dark blue box); and finally, (4) technical and market factors interact bi-directionally (double-headed arrow between dark blue box and grey box). Taken together, political, techno-economic, technical, and market factors shape the configuration of social acceptance (green box), through a series of direct and indirect interactions.

7. Conclusions

To date, a limited number of studies have addressed specific dimensions of the DHT; rarely connecting the interactions between barriers to sustained political support, low-carbon production, cost factors, technical feasibility, technology innovation, market development, and social acceptance. In response, this analysis set out to enrich scientific and policy discussions around the role of hydrogen in the broader energy transition [38,125,353], through advancing both theoretical and empirical understanding on the topic.

As key stakeholders continue to shape the configuration of prospective hydrogen futures across different geographical scales, more integrated research efforts [354] are required to mobilize the power of multi-disciplinary insights [355], in alignment to the pressing need for an accelerated [356] and just energy transition [26,309]. By adopting a socio-technical transition framework – grounded in a multi-level approach – this paper has responded to the call for more holistic research on HESs [63,75], which is critical to comprehensively assessing barriers to the hydrogen economy [357]. Ultimately, this contribution reflects the need for multi-scalar, whole-systems thinking [358,359] to support robust energy governance for the DHT and the wider energy transition.

Section 3 provides the research community with a clear and comprehensive framework for engaging with socio-technical systems thinking in a more tangible way, which has been put into practice in Section 5. The findings affirm that the socio-technical feasibility of low-carbon energy transitions rests on overcoming hard and soft barriers in parallel [89,147], with the aim of coupling techno-economic feasibility [71] to social acceptance [132]. The pathways identified in Fig. 13 hold equally for several other emerging RESs and RETs, whereby effective policy mechanisms are needed to drive early upscaling and market formation; helping to facilitate business models and market acceptance towards an optimal balance between supply-push and demand-pull measures [360,361].

Importantly, observations presented within this analysis can provide critical lessons for developing HESs in other countries. The UK case study, through its twin-track context, can help accelerate the learning curve for other nations that are potentially well-suited to pursuing a blue hydrogen pathway due to aging natural gas infrastructure, such as the Netherlands [362] and Italy [363]. Similarly, European nations with stronger prospects for green hydrogen such as France [364], Germany [302], and Spain [365] can take stock of the identified barriers to scaling up electrolysis production, and related challenges around the green hydrogen supply chain [366]. In either scenario, where feasible, governments must seek pathways to accelerating the pace and scale of domestic hydrogen production, infrastructure development, and demonstration projects, while also engaging the public in developments around these activities.

The study has also drawn significant attention to the conundrum around hydrogen storage, which is often overlooked in discussion around production targets. By accounting for the wider aspects of the techno-economic dimension, policymakers yet to launch their national hydrogen strategies can (re-)evaluate their country's respective potential for developing a hydrogen economy, and what configuration (sectors and scale) and color (blue, green, or other) this may entail. Other key players shaping the prospective global hydrogen economy – including frontrunner countries that otherwise dwarf the UK such as Australia and Canada – can likewise benefit from adopting a multi-level and whole-systems approach when assessing the viability of hydrogen for domestic decarbonization and other uses across different regions [73,367], which may include industrial clusters, urban areas, and off-grid locations.

Finally, many of the findings presented here are directly transferable to other emerging low-carbon energy sources and technologies. For example, the market for domestic micro-generation technolgies [370,371] such as heat pumps [368,369], as well as energy storage technologies [372,373] and innovative energy services (IES) [381], face many of the same barriers discussed throughout this paper [368,369].[48] Acceleration the market diffusion of heat pumps is crucial to the UK's decarbonization agenda; reflected by a national target of 600,000 installations per year by 2028, equivalent to a 20-fold increase compared to installations in 2019 [44]. While the UK is a notable laggard in heat pump adoption, parts of Europe face similar hurdles to increasing the market penetration of heat pumps, as well as solar photovoltaic (PV) panels [374]. Given the fundamental importance of UHS to the fulfilment of national hydrogen strategies [383,384], it is also evident that identified barriers and risks will apply to different extents for other subsurface activities linked to heat decarbonization, such as geothermal energy [375,376], and as previously discussed, CCS.

7.1. Limitations of study and future research agenda

Energy scholars can build on this analysis by testing the proposed framework in different national contexts, as well as other sectors of the hydrogen economy. To proceed with this task, it is important to first recognize the limitations of the study, which also helps identify areas for future research. As discussed in Section 2, one notable drawback is the lack of academic studies on soft barriers to the DHT, especially political and market barriers. Encouragingly, research on the social acceptance dimension is on the rise, although public and consumer awareness remain largely overlooked in the UK Hydrogen Strategy.[49] Relatedly, the review of market barriers in Section 4.4 draws partly on the 2016 report prepared for the Department of Energy & Climate Change (DECC)[50] [112], which is now somewhat outdated given the recent proliferation around hydrogen. In response, a similar study engaging with appliance manufacturers and trades bodies should be undertaken to reassess stakeholders' perspectives. Beyond some limitations related to the literature review materials, this paper lacks a significant contribution in, at least, the following three areas:

- While the UK Hydrogen Strategy frames much of the discussion, this study does not provide a one-to-one analysis to measure the extent to which different barriers have been engaged with by policymakers to date.
- The spatial dynamics of the hydrogen transition are acknowledged, but no in-depth analysis is provided to flesh out key implications based on primary data, such as geospatial maps and regional census statistics.
- Although the importance of environmental impacts is highlighted in several places, there is limited comparative evidence presented to better contextualize the implications of different hydrogen production pathways.

In addition to addressing these limitations, moving forward, researchers should aim to advance knowledge on at least four important

[48] See Fig. 6 in [368] for a visualization of barriers to heat pump deployment.
[49] The topic is discussed briefly in Section 2.5.3 of the strategy.
[50] Merged with the Department for Business, Energy & Industrial Strategy (BEIS) in 2016.

aspects of the socio-technical transition to domestic hydrogen:

(1) Distilling how barriers to respective hydrogen production pathways (e.g. blue and green hydrogen in the UK) can be tackled in a holistic way that promotes synergies which yield net benefits for the hydrogen economy and society.
(2) Mapping interactions between socio-technical factors and key actors to understand HETs at a whole-systems level [382], which is critical to facilitating stakeholder symbiosis.
(3) Examining the potential convergence and divergence of decarbonization pathways for heating and cooking according to space, scale, and geography [377,378], and how this configuration may (re-)define the concept of a hydrogen home.
(4) Conducting comparative cross-country studies of socio-technical barriers to gauge how international hydrogen backbones can be established and consolidated, especially in view of the current geopolitical landscape around natural gas supplies [379].

This final objective is a clear by-product of advancing knowledge on the first three fronts. It presupposes that comparative research will first be carried at the national level, for example, across different UK industrial clusters. In view of the emerging 'techno-socio-economy nexus' for HESs [380], international case studies should become a clear focal point for energy transition scholars and the wider research community.

This study was motivated to engage energy transition scholars, hydrogen experts, and policymakers interested in the socio-technical parameters of the DHT and broader hydrogen economy. As HESs continue to be re-envisioned by technologists, scientists, and other parts of society, all sides of the actor-network must learn from the past to ensure that this era makes the 'true dawn' of the global hydrogen economy. Above all, realizing domestic hydrogen futures will require a radical repurposing of pipelines, policies, and public perceptions.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualization, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.120850.

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APPENDIX B. Homes of the future: unpacking public perceptions to power the domestic hydrogen transition

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Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Conceptualisation, Writing – review & editing, Supervision.

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Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition

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ABSTRACT

Decarbonization in several countries is now linked to the prospect of implementing a national hydrogen economy. In countries with extensive natural gas infrastructure, hydrogen may provide a real opportunity to decarbonize space heating. While this approach may prove technically and economically feasible in the long-term, it is unclear whether consumers will be willing to adopt hydrogen-fueled appliances for heating and cooking should techno-economic feasibility be achieved. In response, this paper develops an analytical framework for examining hydrogen acceptance which links together socio-technical barriers and social acceptance factors. Applying this framework, the study synthesizes the existing knowledge on public perceptions of hydrogen and identifies critical knowledge gaps which should be addressed to support domestic hydrogen acceptance. The paper demonstrates that a future research agenda should account for the interactions between acceptance factors at the attitudinal, socio-political, market, community, and behavioral level. The analysis concludes that hydrogen is yet to permeate the public consciousness due to a lack of knowledge and awareness, owing to an absence of information dissemination. In response, consumer engagement in energy markets and stronger public trust in key stakeholders will help support social acceptance as the hydrogen transition unfolds. Affordability may prove the most critical barrier to the large-scale adoption of hydrogen homes, while the disruptive impacts of the switchover and distributional injustice represent key concerns. As a starting point, the promise of economic, environmental, and community benefits must be communicated and fulfilled to endorse the value of hydrogen homes.

1. Introduction

Since the idea of a global 'hydrogen economy' [1] was introduced in the 1970s [2], the hydrogen revolution has been met with a series of 'false dawns' [3]. Despite past setbacks, the ensuing threat of climate change has propelled renewed action towards achieving this holy grail of the energy transition [4]. Around the world, hydrogen technologies are increasingly recognized as critical for securing a decarbonized future [5]. Accelerated policy action is underway in several countries [6,7] as reflected by the emergence of national hydrogen strategies [8–12].

Australia's National Hydrogen Strategy was released in November 2019 [8]; setting out 57 recommendations for the government, arguably with a stronger focus on economic goals than climate targets [13]. The European Commission (EC) released its *hydrogen strategy for a climate-neutral Europe* in July 2020 [14], while policy developments are underway in several western European countries [15]. In the build-up to the 26th United Nations (UN) Climate Change Conference of the Parties (COP26) in Glasgow [16], the UK made clear its hydrogen ambitions. The Scottish Government released its *Hydrogen Policy Statement* at the end of 2020 [17], with the *UK Hydrogen Strategy* published in August 2021 [18], ahead of the *Heat and Buildings Strategy* in November 2021 [19]. Ultimately, strategic decisions on the role of domestic hydrogen in the UK are set to be taken in 2026 based on a larger evidence base, which includes results from a hydrogen neighborhood by 2023 and village trial by 2025 [19].

Alongside national strategies, international initiatives and partnership agreements are strengthening research and development (R&D) capacity, and the investment landscape for the global deployment of renewably produced hydrogen [20]. Notably, Mission Innovation (MI) is leading the charge to deploy at least 100 "large-scale integrated clean hydrogen valleys" worldwide this decade [21]. Conservatively, the advent of a global hydrogen economy appears set in motion to support climate change mitigation [22,23], with strong prospects also emerging in the Asia-Pacific region [24]. Importantly, the hydrogen transition promises energy security benefits for countries that can secure a first

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Abbreviations

ASHPs	Air Source Heat Pumps
ARENA	Australian Renewable Energy Agency
BEIS	Department of Business, Energy & Industrial Strategy
BP-IC	BP-Imperial College
CCC	Committee on Climate Change
CHP	Combined Heat and Power
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
COP	Climate Change Conference of the Parties
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
DGA	Decarbonised Gas Alliance
EC	European Commission
ENGOs	Environmental Non-Government Organizations
FCVs	Fuel Cell Vehicles
GAD	Gas Appliance Directive
GDNO	Gas Distribution Network Operator
GHG	Greenhouse Gas
GWP	Global Warming Potential
GSHPs	Ground Source Heat Pumps
HESs	Hydrogen Energy Systems
HET	Hydrogen Energy Technology
HFCEVs	Hydrogen Fuel Cell Electric Vehicles
HFCVS	Hydrogen Fuel-cell Vehicles
HFS	Hydrogen Fueling Station
HSE	Health and Safety Executive
IGEM	Institution of Gas Engineers and Managers
kgCO2,eq/MWh	Carbon dioxide equivalent in kilograms per megawatt hour
LCA	Life Cycle Assessment
MCDM	Multi-Criteria Decision-Making
MI	Mission Innovation
MPs	Members of Parliament
MSW	Municipal Solid Waste
NIMBY	Not-In-My-Back-Yard
NO_X	Nitrogen Oxides
N_2O	Nitrous Oxide
OFWs	Offshore Wind Farms
Ofgem	Office of gas and electricity markets
O3	Ozone
PtG	Power-to-Gas
RESs	Renewable Energy Resources
RETs	Renewable Energy Technologies
R&D	Research and Development
SMR	Steam Methane Reformation
SEM	Structural Equation Modeling
SVTs	Standard Variable Tariffs
UN	United Nations

mover advantage, especially those with extensive renewable energy resources (RESs) [25,26].

Despite cause for optimism, technical factors [27,28], market dynamics [29,30], the political environment [28,31], as well as the underlying socio-cultural landscape [32] could constrain national and global objectives for the hydrogen economy. Evidence suggests that cultural and behavioral barriers may stall climate change action at the community and household level [33–35], weakening the prospect of securing low-carbon 'energy futures' [36]. However, in the context of Hydrogen Energy Systems (HESs), end-users have mostly been perceived as a barrier to deployment, or otherwise regarded as another parameter for assessment, as opposed to "a resource for the design" of the system [37]. This characterization overlooks the importance of understanding the dynamics of social acceptance for enacting desirable energy transition pathways [38].

Adopting a socio-technical systems perspective [39,40] this paper contends that public perceptions will largely dictate whether the hydrogen transition is supported by a requisite level of social acceptance, which may prove equally important as technological feasibility [12,41]. It follows that the "human dimension" of the hydrogen transition must go hand-in-hand with "technical logistics" to enable the adoption of hydrogen home appliances [42]. Inadequate levels of social acceptance may very well present the greatest barrier to the realization of the global hydrogen economy [43].

1.1. Socio-technical systems thinking for hydrogen homes

Geels' seminal contribution [44] shifted the analytical focus from "sectoral systems of innovation and production"[1] [45] to a socio-technical systems perspective, which better accounts for the role of end-users in the coevolution of technology and society. In response, researchers have increasingly adopted a socio-technical transition framework approach [46–51] to analyze the ways in which concrete (i.e. the 'physical', 'material' and 'technical' [52]) and abstract factors [53] may influence the speed and duration of the energy transition [54]. Although the broader hydrogen transition has been examined through this lens [55–59], few studies have concentrated exclusively on the prospect of 'hydrogen homes'; composed of hydrogen-fueled appliances for domestic space heating, hot water and cooking [60].

As with natural gas-based appliances [61], and other large-scale energy systems [62–64] that serve the needs of society [65], the socio-technical system for hydrogen homes will be sustained by a range of interdependent factors, which may determine the pace and nature of the transition. Although the emerging literature on the feasibility [66,67] and determinants of domestic hydrogen acceptance [42,68,69] recognizes that a range of socio-technical barriers exist, limited critical analysis has been undertaken to unpack the significance of these findings. While the domestic hydrogen transition faces a distinct set of socio-technical barriers which may be viewed differently across parts of society, there is a significant knowledge gap concerning how and why perceptions may vary at the community and household level. In response, this paper answers the call to increase social science engagement with consumer preferences for hydrogen homes [60,70–72].

As a first step towards addressing this knowledge gap and elevating the role of end-users in hydrogen homes, this article sets out to determine what is currently known and what needs to be understood about barriers to social acceptance in the future if candidate countries are to deploy hydrogen homes at scale. Accordingly, the aims are as follows: (1) to analyze, through literature review, the key socio-technical factors shaping public perceptions of the domestic hydrogen transition; (2) to rank the critical factors of domestic hydrogen acceptance; and (3) to map a future research agenda for overcoming barriers to domestic hydrogen acceptance.

Following this introduction, Section 2 describes the methodology and charts the literature on public perceptions of the domestic hydrogen

[1] Malerba [45] defines a sectoral system as "a set of products and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products.".

transition. Section 3 presents the theoretical approach employed in this study based on the five dimensions of domestic hydrogen acceptance, as visualized in Fig. 3. Applying this analytical framework, Section 4 synthesizes the existing literature on public perceptions of socio-technical barriers to the domestic hydrogen transition. Next, Section 5 provides a ranking of the critical factors of domestic hydrogen acceptance and maps a future research agenda to help accelerate the social acceptance of hydrogen homes. The concluding section highlights the key findings and contribution to the energy transitions literature.

2. Materials and methods

Following Sovacool et al. [73] and Scovell [12], this paper undertakes a structured narrative review by applying specific search criteria to explore the literature on domestic hydrogen acceptance. A narrative review aims to identify and summarize previous publications, while highlighting new study areas yet to be addressed [74]. Social science research on domestic hydrogen is a subset of the wider literature on hydrogen acceptance [73], which this study draws on as supporting evidence to the case of hydrogen homes. This approach is consistent with the underlying objective to map a future research agenda by synthesizing the existing evidence base. A more systematic literature review could not be undertaken due to the relatively small sample size (N = 17), however, the initial scoping and screening procedures followed systematic methods.

There is an emerging body of literature focused on the social acceptance of hydrogen appliances for home use and the acceptability of domestic hydrogen in the broader energy transition [60,71,72,75,76]. However, the number of peer-reviewed articles on 'hydrogen social acceptance' remains dwarfed by studies on the 'hydrogen economy' and 'renewable hydrogen' [77]. Moreover, to date, hydrogen acceptance research has engaged almost exclusively with transportation applications [68,77], consisting mainly of studies focused on trials/demonstrations of hydrogen fuel-cell vehicles (HFCVS), and associated infrastructure [71,77,78] such as hydrogen fuel stations [12]. While this literature has a comparatively rich base of international research on public perceptions [68,77] dating back to the 2000s [79–84], studies on domestic hydrogen acceptance are a recent development, pioneered mainly by researchers in the UK, Australia, and parts of Europe [68–70, 85–87].

Emodi et al. [71] systematically reviewed the literature on hydrogen acceptance, retrieving 43 valid articles for the period 2008–2020, which included five papers on domestic hydrogen [58,66,73,87,88] since 2018. More recently, Scovell [12] reviewed 27 quantitative studies exploring the relationship between psychological factors and Hydrogen Energy Technology (HET) acceptance. The study underscored the need to examine hydrogen acceptance factors and moreover, the reasons and extent to which acceptance levels vary between people. Elsewhere, Kar et al. [78] used bibliometric analysis to analyze 1275 articles published between 2016 and 2020, showing that research on the "hydrogen economy" has accelerated, with the phrase gaining better acceptance in Asian countries. Adopting a socio-technical systems approach, Griffiths et al. [39] carried out a critical and systematic review of industrial developments regarding low-carbon hydrogen. Additionally, Edwards et al. [90] undertook a multi-disciplinary review focused on "the status of hydrogen technologies in the UK," calling for further research focused on public acceptance.

This study set out to retrieve the full evidence base on domestic hydrogen acceptance from across the academic and grey literature to provide a state-of-the-art review. The following sections explain the data collection procedure, which involved accessing articles from the four databases: Scopus, Web of Science, the Hydrogen Knowledge Centre, and Google Scholar. The search resulted in a total of seventeen studies for final review (see Fig. 1).

2.1. Scopus and Web of Science

Using the Scopus database, an initial search was carried out with the following key words: "hydrogen heating" OR "hydrogen acceptance" OR "hydrogen homes." The search returned only 76 results, whereas a subsequent search with the phrase "hydrogen transitions" returned 128 results. Given the relatively low numbers, a further search was implemented following Emodi et al. [71]: "social acceptance" OR "public acceptance" OR "consumer acceptance" OR "household acceptance" AND "hydrogen." This search was successful in returning 241 results. A parallel search using the key words "hydrogen transitions" OR "hydrogen acceptance" OR "hydrogen heating" OR "hydrogen cooking" OR "hydrogen homes" also returned 241 results.[2]

Screening the first 241 articles (based on Emodi et al. [71]) retrieved just one study on hydrogen acceptance in 2015 [91], compared to four studies in 2016 [92–95]. Given this trend, the date filter was reset to 2016 (N = 105). Three more studies on hydrogen acceptance were retrieved from 2017 [89,96,97], of which Oltra et al. [89] included a focus on stationary home fuel cells. A further 18 studies were retrieved with a relevant framing on hydrogen acceptance [12,24,43,71,98–111], however, none of these focused on domestic applications. Screening the remaining 241 articles based on the second key word search ("hydrogen transitions" OR "hydrogen acceptance" OR "hydrogen heating" OR "hydrogen cooking" OR "hydrogen homes") located two studies in 2016 [112,113].[3] From 2017 onwards, three papers on hydrogen acceptance were retrieved, with two including an explicit focus on the residential sector [60,75].

Given these results, a follow-up search was carried out in Web of Science with the date filter set to 2017, using the term "hydrogen acceptance" in the Title, Abstract or Author Keywords, which provided 276 results. The breakdown underscored the dominance of technical literature on hydrogen technologies and the deficiency of studies on social acceptance aspects. The top six categories defined by Web of Science ('Energy Fuels,' 'Chemistry Physical', 'Electrochemistry', 'Materials Science Multidisciplinary', 'Environmental Sciences', 'Chemistry Multidisciplinary', and 'Green Sustainable Science Technology'), represented 89% of the search results (N = 247). With the removal of any duplicates, five studies passed the screening criteria for further consideration [114–119]. Although valuable as supporting evidence, none of these studies provided a specific focus on domestic hydrogen acceptance.

2.2. Hydrogen Knowledge Centre

Given the limited number of studies retrieved from Scopus and Web of Science, a subsequent search was conducted using the Hydrogen Knowledge Centre database[4]; a digital resource hub launched in March 2021 by the Institution of Gas Engineers and Managers (IGEM) to support understanding of the hydrogen transition. The repository provides access to nearly 3000 sources on hydrogen (in English) and responds to the need for a "|hydrogen industry knowledge-sharing platform" [120].

Selecting the key words "Consumer & End Users" and "Hydrogen for Domestic Applications" from the drop-down menu produced 129 results, dominated by studies in the United Kingdom (N = 64) and Australia (N = 21). The titles and abstracts were carefully screened to source the first available study with a definitive focus on domestic hydrogen acceptance; published in November 2018 and commissioned by the Committee on Climate Change (CCC) [121]. One month later, the Australian Renewable Energy Agency (ARENA) released a report on public perceptions of hydrogen for energy, which included a focus on domestic heating and cooking [68]. Overall, the Australian public appeared to be

[2] No duplicates were reported.
[3] Resetting the data filter to 2016 reduced the search results to N = 51.
[4] https://www.igem.org.uk/hydrogen-knowledge-centre/.

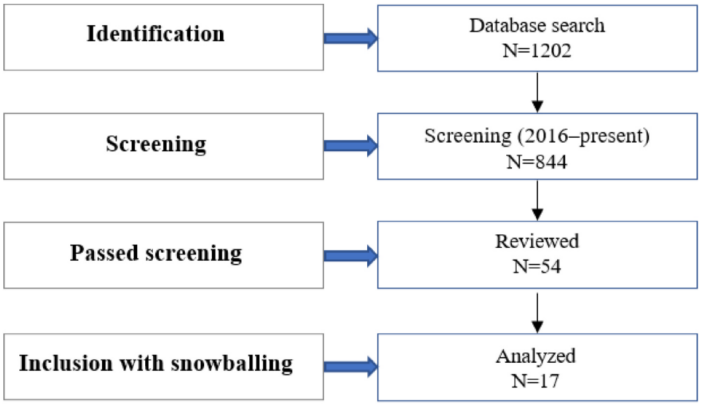

Fig. 1. Data collection procedure.

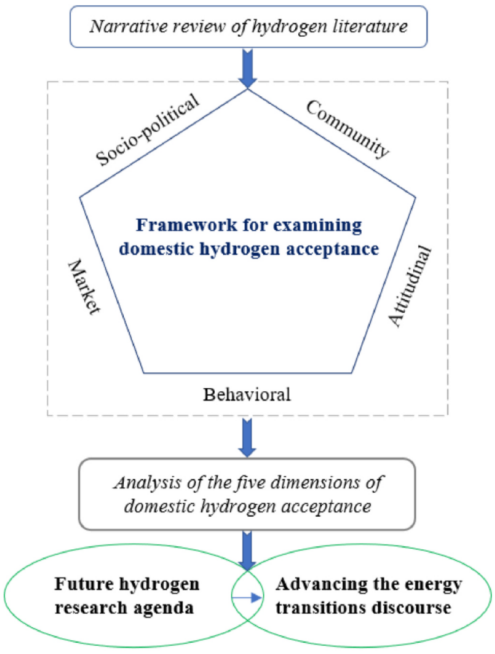

Fig. 2. Research procedure and methodology.

"positively cautious" about developing a national hydrogen industry and economy [68].

Refining the search to English studies published since November 2018 produced 97 results.[5] At the end of the screening, nine additional studies had been retrieved, six of which presented primary data on domestic hydrogen acceptance as required for final inclusion [42,68,69,87,88,122]. While this database search proved fruitful, the last study dated to June 2020 [69], which suggested more recent literature could still be retrieved.

2.3. Google Scholar and snowballing

Two final key word searches were performed in Google Scholar with the filter "2017 to present": "hydrogen transitions" (N = 236); and "hydrogen transitions" OR "hydrogen acceptance" (N = 315). Given that the second search term increased the results by 33%, these studies were scanned. In total, seventeen studies passing the first screen [31,37,39,70,72,78,90,117,123–131]. Of note, Martin et al. [37] reviewed 152 publications on HESs using a human-technology relationship framework. The authors called for more research on hydrogen use in the residential sector, with a shift towards a more user-focused approach to design a desirable hydrogen system, as opposed to making the system acceptable to consumers following technology deployment. However, this search returned limited results on domestic hydrogen acceptance once duplicates were removed, namely four studies [70,72,123,128].

Encouragingly, purposeful snowballing sampling [132] helped retrieve three additional studies [76,77,86]. Further analysis revealed the following connections [12,77]: are studies from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia [86]; is ARENA's follow-up study to Refs. [68,76] directly followed [89] with a focus on hydrogen acceptance in Europe; three UK studies [60,75,87] are authored by Scott and Powells (Newcastle University); while [69,123] are studies from Leeds University and Leeds Beckett University, respectively, which follow technical work on the Leeds City Gate H21 project [66]. This snapshot reveals a degree of continuity in domestic hydrogen studies (see Table 1), but also limitations in research diversity and scope.

In addition to the studies presented in Table 1, this paper draws on extensive evidence from the literature on renewable energy (RE) acceptance [85,133–140], energy justice [141–146], and 'hydrogen futures' [29,55,57–59,147]. This literature helps contextualize the findings on hydrogen acceptance within the broader energy transitions discourse [148–150]. To derive an analytical framework grounded in theories from the behavioral and social sciences (see Fig. 2), the paper integrates scholarly contributions to 'the triangle of social acceptance of renewable energy innovation' [135] and Social Practice Theory [151], as well as the Energy Justice [145] and Energy Cultures framework [152].

[5] The distribution of studies was almost equal for each of the keywords.

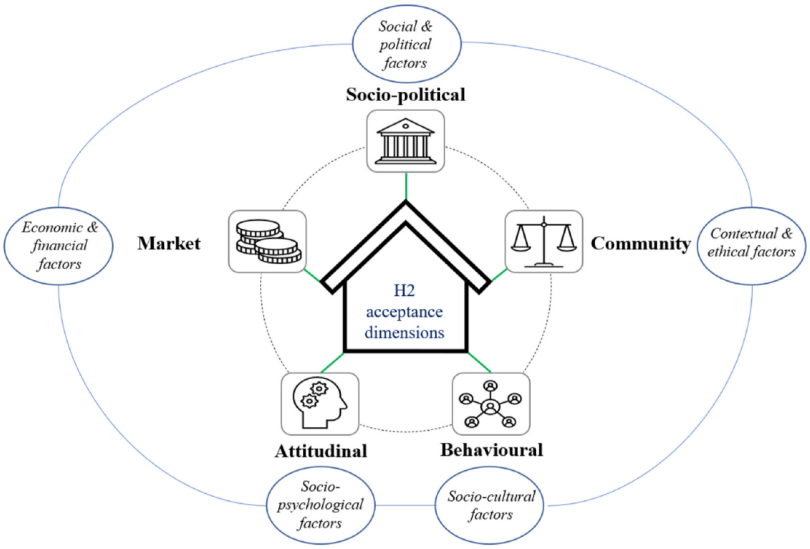

Fig. 3. Analytical framework linking dimensions and factors of domestic hydrogen acceptance based on Gordon et al. [153]. The framework links together the five dimensions of domestic hydrogen acceptance with their corresponding factors.

3. Socio-technical barriers and the five dimensions of hydrogen acceptance

Based on the work of Gordon et al. [153,154],[6] this section describes the proposed theoretical approach for examining socio-technical barriers to domestic hydrogen acceptance (see Fig. 3). Through mapping respective barriers to attitudinal, socio-political, market, community, and behavioral acceptance, the analytical framework contributes to socio-technical systems thinking [44] on the energy transition [62,63], and answers the call to elevate the role of end-users in HESs [37].

3.1. Attitudinal acceptance

Attitudinal acceptance operates at the micro-scale configured by factors such as knowledge, awareness, perceptions, and attitudes [85,133], each of which play a part in shaping how end-users perceive the costs, benefits, and risks associated with sustainable energy technologies [133]. Perception can be defined as what consumers think or associate with hydrogen technologies, whereas attitude represents a more definitive judgement about whether a hydrogen transition is desirable [83].

At present, the benefits of domestic hydrogen remain poorly understood by end-users [121] due to low levels of knowledge and understanding [155]. Furthermore, when consumer benefits are tied up with abstract environmental gains related to climate change mitigation, individuals are more likely to prefer the 'least-worst' option or to otherwise remain indifferent [121]. Such a scenario would inhibit a transition to domestic hydrogen, as active consumer acceptance is more likely to support the uptake of low-carbon heating technologies [134]. In turn, attitudinal acceptance is evaluated by gauging public knowledge and awareness of hydrogen, safety perceptions, affective response, and the impact of information on consumer attitudes.

[6] Ref. [153] is currently under review by Applied Energy. Ref. [154] was accepted as a conference paper for the 13th International Conference on Applied Energy (ICAE) and has been invited to the *Special issue*, SI:ICAE 2021.

3.2. Socio-political acceptance

As a key component of the "dynamic political feasibility space" of decarbonization pathways [156], socio-political acceptance is contingent on the ability of regulators, legislators, policymakers, and other key stakeholders to craft effective national policies to foster community, market, and public acceptance of renewable energy technologies (RETs) [135,136]. Trust, fairness, and legitimacy have been identified as key factors of socio-political acceptance [135,157], which broadly reflect the preference for a 'just energy transition' [123,141,142]. As stated by Aditiya and Aziz [24], "public trust determines the severity of social friction that may heavily influence the hydrogen program."

Socio-political acceptance for an emerging technology such as domestic hydrogen can be considered as an extension of broader acceptance for renewable and low-carbon energy technologies, including other hydrogen applications such as fuel cell vehicles (FCVs). To an extent, hydrogen acceptance can be extrapolated from the public's general disposition towards the net zero agenda. Accordingly, socio-political acceptance is firstly considered in terms of consumer engagement and trust in the energy transition. Thereafter, public perceptions are examined in relation to hydrogen production methods, decarbonization pathways, environmental impacts, and trust in key actors and stakeholders.

3.3. Market acceptance

Sovacool and Ratan [136] explain market acceptance according to the interactions between investors as technology supporters and consumers as technology adopters, which plays out "at a meso level between national politics and local communities." It follows that market acceptance for domestic hydrogen end-users will depend on both macro- and micro-scale factors. Additionally, appliance development will depend on international markets as countries compete for a frontrunner advantage in the global hydrogen economy [31].

Market acceptance at the macro-scale is shaped by economic impacts across the national, regional, and local levels. In contrast, market

Table 1
This table provides a summary of social science research on domestic hydrogen acceptance. In total, 17 studies were retrieved since 2017. Nine studies were carried out in the UK, five in Australia, and three in Europe. Twelve items belong to the grey literature, five are journal publications, and one is a thesis paper. Eleven of the studies focused on domestic hydrogen acceptance, while seven items provided selective findings within the context of the broader hydrogen transition.

Study	Location, research type, and sample size	Research scope
[89]	Nationally representative only survey using quota sampling EU: Belgium, France, Germany, Norway, Slovenia, Spain, UK; N = 7148	Analyzes public attitudes towards stationary residential fuel cells (micro-combined heat and power (CHP)) and hydrogen fuel cell electric vehicles (HFCEVs) to understand cross-country variations.
[76]	Nationally representative only survey using quota sampling EU: Belgium, France, Germany, Norway, Slovenia, Spain, UK; N = 7148	Examines attitudinal acceptance by analyzing consumer and citizen reactions to information provision on hydrogen fuel cell technologies.
[121]	a) Nationally representative online survey UK; N = 1029 b) Four focus groups London and Edinburgh; N = 29	Assesses the public acceptability of hydrogen boilers and heat pumps, focusing on attitudinal differences between socio-demographic groups.
[68]	a) Nationally representative online survey Australia; N = 2785 b) 10 focus groups South Australia and Victoria; N = 92	Explores the Australian public's response to the burgeoning opportunities of hydrogen for export, transport, and domestic use; focusing on potential barriers and enablers to a national hydrogen transition.
[77]	Interviews with industry and government representatives from across the hydrogen energy value chain Australia; N = 14	Examines stakeholders' experiences with public perceptions of hydrogen, with the goal of advancing "socially responsible practices and policies" for developing Australia's hydrogen economy; outlining the key issues that could affect the current and future level of acceptance and adoption of hydrogen energy.
[88]	9 focus groups Australia: Queensland (Townsville), Victoria (Warrnambool), and Northern Territory (Darwin);[b] N = 72	Investigates the potential for hydrogen in three regions of Australia and the country more broadly, with a focus on public perceptions and best practice for community engagement.
[123]	a) Online survey Leeds and Teesside; N = 578 (548 from Leeds) b) Semi-structured interviews with key stakeholders purposive sampling; N = 30	Provides a regional perspective of public perceptions regarding the development and use of hydrogen energy technologies as an energy vector to decarbonize processes within and between Leeds and Teesside.
[42]	4 focus groups with consumers from different housing segments connected to the gas grid[a] England: Manchester and Birmingham; N = 39	Assesses consumer perspectives on the disruption and costs impacts of a hypothetical hydrogen switchover, focusing on logistical and welfare issues.
[87]	Nationally representative online survey UK; N = 742	Designs and deploys an online survey, collecting quantitative data on public perceptions of hydrogen and hydrogen blending in the UK.
[60]	Paper-based survey and follow-up interviews (cafés/coffee shops) 10 different locations in the North East of England; N = 100	Examines how the physical and chemical properties of hydrogen may impact the 'gas-energized' social practices of cooking and heating.
[75]	a) Online survey, representative of the HyDeploy2 trial areas North of England; N = 700 b) Paper-based survey conducted in cafés Nine towns in the North of England; N = 102	Elicits and evaluates public perceptions of hydrogen and hydrogen blending in the UK in relation to theories of social practice, energy justice, and place attachment
[122]	a) 50-question online poll UK; N = 2000 b) 4 focus groups North of England and Greater London; N = 32	Examines public opinion on the environment and climate change; and views on changes to home heating, industry, and transport for achieving net zero; explores attitudes towards decarbonization pathways and policy recommendations for home heating, industry, and transport.
[69]	a) Nationally representative online survey UK (Leeds, Monmouthshire, and Birmingham); N = 1027 b) Discovery interviews N = 12 c) Deliberative workshops	Explores public perceptions of changing the UK domestic fuel supply to 100% hydrogen; examines beliefs about the environment, inconvenience and costs, safety, and potential economic impacts.
[86]	Nationally representative online survey Australia; N = 3020	Examines public perceptions towards hydrogen for domestic use (n = 1507), and export and future energy considerations (N = 1513)
[72]	Two-hour online workshop with participants from academia, government, industry, and advocacy organizations Australia; N = 22	Investigates the current knowledge and knowledge gaps regarding the potential impacts of Australia's domestic hydrogen transition on energy vulnerability.
[128]	Online survey Republic of Ireland, N = 115 Semi-structured interviews with survey respondents (N = 8)	Examines how the public perceives hydrogen as an energy vector, outlining potential obstacles to social acceptance.
[70]	Online survey Discrete choice experiment and a mixed logit model France; N = 202	Analyzes consumer preferences for hypothetical hydrogen-based energy storage systems, considering the behavior of households vis-à-vis hydrogen as a new energy carrier, and acceptance of supply and management methods.

[a] Two with owner-occupiers, one with private landlords, and one with a mixture of tenants (private, social, student).
[b] Two focus groups were held with the general public in each city (N = 52) and 1 focus group was held with influential stakeholders in each city (N = 20).

acceptance at the micro-scale focuses on the household level, where willingness to pay for new technologies is largely determined by cost and financial factors. These scales or levels are considered by reviewing how the public perceives issues concerning economic impacts, technology choice, and financial costs.

3.4. Community acceptance

Making a seminal contribution to the conceptualization of social acceptance of RETs, Wüstenhagen et al. [135] explained community acceptance in terms of the willingness of local stakeholders to invest in new energy projects or appliances, which is largely shaped by perceptions of fairness and justice regarding the distribution of costs and decision-making processes. These perceptions are strongly influenced by the provision of procedural and distributional justice, which represent two of the three tenets of the Energy Justice framework [144]. The framework was developed from environmental justice research and is designed to "foster analyses of unfair energy policies and projects" [158].

Procedural justice is determined by the informational aspects of energy developments, decision-making processes, and the degree of stakeholder participation in the planning of rules and laws [143,145,159], whereas distributional justice depends on how the costs and benefits of technology adoption are distributed across society [146,159,160]. Completing the triumvirate [145], recognition justice is concerned with the provision of full and equal political rights as a mechanism to help prevent discriminatory practices and the potential for 'misrecognition' [161], which may take shape through cultural domination,

non-recognition, and disrespect [162].

Historically, justice concerns have rarely featured prominently in stakeholder planning processes for energy projects [163]. Notably, the geographic distribution of land-based UK renewables has been associated with issues of social injustice [164], reinforcing the need for inclusive and equitable approaches to managing the hydrogen transition. Furthermore, community acceptance research has often adopted a post hoc approach through case studies on local responses to specific project proposals [137]. While there are benefits to such research, case studies of this nature may overlook key decision-making factors; failing to provide insights on how broader contextual factors impact the views of local communities [137]. Here, community acceptance is explored in respect to public perceptions concerning the spatial dynamics of hydrogen communities and the transition at large, in addition to related issues surrounding distributional and procedural justice, and disruptive impacts.

3.5. Behavioral acceptance

Resonating with the Energy Cultures framework – based on beliefs, values, and energy practices [152] – the 'social practice approach' has been proposed for better understanding the daily practices and behaviors associated with energy technologies [75,165]. Social Practice Theory contends that behaviors are an expression of personal choice dictated by beliefs, values, attitudes, and tastes; equating lifestyle habits to a performance of sorts, wherein behaviors become internalized through repetition or practice [151,166]. In respect to understanding new energy practices, Scott and Powells [60] suggest that the "analytical focus" should be shifted to capture how people are likely to behave, as opposed to what they may think or feel. Following Gordon et al. [153], behavioral acceptance is assessed according to interactions between socio-cultural and personal factors, resting on consumer perceptions of hydrogen's disruptive impacts to daily routines during the switchover period, and subsequent changes to the lived experience of heating and cooking.

4. Results

The following sections (4.1–4.5) provide a comprehensive review of the empirical data on domestic hydrogen acceptance, drawing on supportive findings from across both the hydrogen futures and energy transitions literature. Here, and throughout the rest of the paper, a sequential, structured approach is taken by examining attitudinal, sociopolitical, market, community, and behavioral factors.

4.1. Barriers to attitudinal acceptance

4.1.1. Perceptions, knowledge, and awareness of hydrogen

Affective or emotional responses to hydrogen have been shown to shape consumer attitudes, especially in respect to risk perceptions [167,168]. Traditionally, the word 'hydrogen' has tended to evoke a neutral response from the general public [68,88,169,170]. Associations to hydrogen may vary from energy, fuel, gas, element, and peroxide, to renewable, water, bomb, balloon, explosion, flammable, or future technology [88,128]. Consumer attitudes may also take on a neutral framing in some cases. For example, Oltra et al. [89] found a high prevalence for neutral attitudes towards hydrogen home fuel cells in the United Kingdom, Norway, and France. 52% of South Koreans (N = 1000) had neutral attitudes towards hydrogen fueling stations [99], while 73% of UK public participants (N = 4673) had no opinion or a neutral opinion prior to a novel public engagement activity for the hydrogen bike [127]. When neutral associations and attitudes do prevail, this may be due to an underlying lack of knowledge and awareness [87].

Evidence suggests that willingness to adopt low-carbon technologies – understood as willingness to use a technology that is available on the market, given that all user-related aspects remain equal in comparison to conventional energy applications [83] – may be positively associated with knowledge and awareness [42]. Indeed, prior knowledge has been shown to be a significant driver of public support for hydrogen technologies [171], especially in the context of hydrogen transportation [172].

It is well-documented that public knowledge and awareness of hydrogen and its potential commercial applications remains low [81,171,173–175]. Despite some parts of the public proving reasonably knowledgeable about hydrogen [83,94], most studies report low levels of knowledge and awareness (see Table 2). Even in Japan where there is a well-publicized effort to develop hydrogen energy infrastructure [176] as part of the country's Strategic Energy Plan [177], public awareness continues to lag compared to RETs and secondary energy sources [97]. Typically, citizens have limited knowledge about hydrogen production methods [69], safety and storage [15], and may still lack any immediate reference point or daily interaction with hydrogen energy technologies (HETs) [178]. The result is feelings of uncertainty, unfamiliarity, and remoteness concerning hydrogen [75,179,180]. Consequently, current perceptions may prove speculative or tentative at best, while the public remains cautious in their judgements and somewhat skeptical about the hydrogen transition [69,84].

Hydrogen's status as a peripheral technology [75] is especially pronounced in the domestic context where it remains unfamiliar to most of the public [42,77]. Scott and Powells [60] observed that the public has limited knowledge about the physical and chemical characteristics of hydrogen. Furthermore, public perceptions may hinge on how the technical complexity and unfamiliarity of hydrogen appliances compare to other low-carbon technologies for domestic heating and cooking [121].

Despite an underlying consensus that hydrogen knowledge and awareness remain low, there are early indications that hydrogen is starting to enter the public consciousness, albeit gradually [70,76,86]. Damette et al. [70] showed that mainstream hydrogen knowledge appears to have increased compared to earlier studies in 2006 [83] and 2010 [171], while Martin et al. [86] found that subjective knowledge of hydrogen has increased in Australia. Furthermore, self-reported knowledge on hydrogen was higher than in 2021 [86] than in 2018 [68] for five out of six statements. Interestingly, self-reported knowledge on hydrogen production was lower [86].

These findings reaffirm the need to communicate more to the public

Table 2
This table provides evidence on public knowledge and awareness of hydrogen. Overall, hydrogen remains an unfamiliar proposition to society, with the public having limited knowledge.

Source	Findings
[60]	• Two-thirds of survey participants were unaware that hydrogen burns with a near invisible flame
[68, 86]	• Australians had low objective knowledge of hydrogen, especially regarding its characteristics and properties (men answered more questions correctly)
[88]	• Only two focus group participants had heard something about Australia's National Hydrogen Strategy, but neither could provide any additional details
[89]	• Less than 10% of European respondents were familiar with HETs • 59% were unaware about hydrogen's role in energy production and only 25% had heard of residential fuel cells
[121]	• 45% of respondents were unfamiliar with hydrogen appliances or heat pumps • Those with knowledge had limited awareness about decarbonization credentials
[123]	• 36% of respondents (the highest proportion) indicated they 'need to know' more about hydrogen to comment about its role in decarbonizing the economy
[181]	• 88% of survey respondents had never heard of hydrogen boilers; compared to 49% for biomass boilers, 61% for ground source heat pumps (GSHPs) and 75% for air source heat pumps (ASHPs)

about the potential or desirable role of different energy sources in developing the hydrogen economy; without forcing consumers to try to 'crack the hydrogen color code' [182], given its ever-evolving rainbow spectrum [183,184]. As a first step towards counteracting this underlying knowledge gap which may otherwise constrain the domestic hydrogen transition, it is strongly recommended that the public is at least provided with a simple explanation of different hydrogen production methods [121].

4.1.2. Hydrogen safety factors

Hydrogen technology remains a contested topic [147] characterized by blurred representations between 'myths' and 'facts' [185], especially in relation to hazards and risks [186]. Despite obvious risks given its flammability characteristics [187], hydrogen fuel has been used safely in aerospace [188,189], and petrochemical applications [190–192] for several decades [186]. Nevertheless, the safety credentials of hydrogen have been long debated [186,191,193,194] in relation to a range of areas and applications [195] including aviation [196,197] surface transportation [198–200], handling and storage [201–204], industrial uses [205–207], and more recently domestic heating and cooking [42,60,75]. To date, acceptable safety standards have been upheld [185], however, adherence to safety measures is significantly harder to secure and monitor for hydrogen use in residential and commercial applications [208].

While most studies indicate that the safety hazards of hydrogen [195] are roughly equivalent to that of natural gas, gasoline, and other fuels [186,209], it is generally accepted that 'hydrogen blending' – the injection of small quantities of hydrogen into existing natural gas networks [210,211] – will engender potentially new hazards [212]. Hydrogen has distinct physical and chemical properties [60,212], which may present new or greater risks in the domestic environment (see Table 3). Notwithstanding, hydrogen blending has been promoted as a 'practical' and 'non-disruptive' pathway towards securing emissions reduction in residential heating [213].

4.1.3. Public perceptions of hydrogen safety

Hydrogen safety issues extend beyond the technical domain to the socio-cultural dimension, given that the domestic environment is a place of "security and control," which the introduction of new energy technologies should reinforce [219]. Engaging with hydrogen experts and key stakeholders in Germany, Schlund et al. [129] reported a consensus that technical issues, safety concerns, and other risk factors remain a significant barrier to market development and public acceptance of low-carbon hydrogen technologies. Compared to other technologies such as stationary battery storage and biofuel production plants, the public is significantly more concerned about the explosive hazards of hydrogen refueling stations [98], which may lead to opposition on safety grounds especially from households with more family members [99]. Furthermore, hydrogen is often portrayed as a "sensitive gas," which may undermine its status in countries without any direct engagement in hydrogen infrastructure and industrial applications, weakening its role in the global energy transition [78].

In some cases, public concerns over hydrogen safety may supersede other issues such as cost and performance [68]. For example, support for converting the Australian gas network to 100% hydrogen was limited to 38% (compared to 30% for electrification), largely owing to public concern about hydrogen's volatility and flammability [68]. While safety concerns over hydrogen blending proved minimal [68], other studies suggest a mixed picture regarding public perceptions of hydrogen safety (see Table 4). Concerns may revolve around personal safety, environmental impacts, the potential for leakages in hydrogen pipelines and the risks associated with carbon, capture and storage (CCS) [122].

Socio-structural variables such as socio-demographic, socio-economic, and socio-cultural characteristics [103], as well as geographic factors and household differences [99,122] may partly explain variation in safety perceptions. For example, the Decarbonised Gas Alliance (DGA) found that focus group participants from Warrington – an industrial town located in the North West of England – expressed few concerns about safety due to an underlying trust in regulatory practices, whereas participants from Bushey – an affluent commuter town in North London – had more reservations about the safety credentials of hydrogen [122]. While one Warrington resident drew a comparison between CCS and nuclear waste, the consensus from the North West was that hydrogen would not be brought online unless it was deemed as safe as natural gas. Other studies suggest that safety concerns are reduced when public trust in regulation is stronger [68,69,87].

In some instances, consumers may be more preoccupied about the safety levels of CCS than the actual use of hydrogen in their homes [122], highlighting the cross-sectoral implications of hydrogen technology and the importance of community acceptance. Additionally, hydrogen boilers may present less of a safety risk in the eyes of consumers due to their self-contained nature, whereas the exposed, yet invisible flames of hydrogen cooking appliances exhibit a more direct and tangible threat to the domestic environment [60]. Accordingly, households may reject hydrogen as a fuel for cooking unless it burns with a visible or detectable flame, since this feature is regarded as

Table 3
This table identifies technical barriers to the deployment of domestic hydrogen appliances and describes their safety implications.

Characteristics	Safety implications
Near-invisible, pale- blue flame [214] and odorless [75]	Higher risk of fires remaining undetected or propagating due to reliance on proximity to the flame/appliance for sensory awareness [212]
Higher flame speed than natural gas [215]	Increases the propensity for flame flashback whereby the flame burns closer to the appliance, increasing the risk of spillage of combustible mixture and potential explosion [210,215,216]
Higher adiabatic flame temperature than natural gas [217]	Formation of nitrogen oxides (NOx) increases exponentially with adiabatic flame temperature, resulting in higher levels of respiratory health risks [218]

Table 4
This table describes the public's perceptions of hydrogen safety in the UK, Australia, and Europe. Overall, there are mixed views regarding the safety credentials of domestic hydrogen.

Source	Country	Public perceptions of hydrogen safety
[42]	UK	• Most participants felt reassured provided safety tests were carried out. However, concerns remained over several key factors including the combustibility, color and smell of hydrogen gas, hydrogen production and storage
[68]	Australia	• Respondents were mostly unconcerned about the safety risks of natural gas being 'blended' with 10% hydrogen, preferring the use of this term to 'piped' or 'injected'
[75]	UK	• 69% of online survey respondents and 57% of paper survey respondents envisaged no significant impact of hydrogen blending on domestic safety[a] • 35% of paper survey respondents reported positive impacts on safety
[83]	Netherlands	• 70% of respondents would reject hydrogen blending if it proved marginally less safe than natural gas, but still within regulatory limits
[93]	Germany	• Consumers are highly sensitive to the risks associated with hydrogen energy storage

[a] Less than 14% and 8% of participants from the online and paper survey perceived that there would be a negative impact on safety.

paramount to both safety and functionality.[7]

To an extent, negative perceptions of hydrogen could persist due to its iconography with war [167,220] and explosive accidents [221,222], which may prove challenging for some citizens to overlook [223]. However, such attitudes may lie with inflated concerns [77] attributed to a fear of the unknown [15,209], as opposed to more credible fears about hazards and risks [224]. While the importance of socio-structural factors has been illustrated, concerns over hydrogen safety appear to also stem from an underlying lack of public awareness and knowledge [60]. Notwithstanding, to strengthen social acceptance at both the community and household level, it is first necessary to demonstrate that hydrogen technology and infrastructure is technically feasible [208], with a full-scale conversion to hydrogen ensuring at least the same safety levels as natural gas networks [69]. The safe capture and sequestration of carbon should also be proven to avoid the risk of public opposition and costly delays [69].

4.1.4. Information provision and experience with hydrogen energy technologies

The provision of information, whether factual [225] or hypothetical [42], can have a significant impact on how participants perceive climate change [226] and energy technologies [227] including hydrogen [86]. Information provision may motivate consumer interest in the costs, benefits, risks, and performance of hydrogen technologies [178]. Whether knowledge is 'perceived' (i.e. subjective) or 'actual' (i.e. objective), it typically enables consumers to feel more confident about making informed decisions [68]; acting as a driver for decision-making and leading to support if aligned to the positive aspects of hydrogen technologies such as their potential environmental benefits [87].

Several survey studies have highlighted the impact of information framing on hydrogen acceptance. Molin [228] found that 'colored' information (i.e. positive, negative and neutral framings) had a direct impact on hydrogen perceptions, influencing consumer attitudes and willingness towards using hydrogen in the Netherlands. In Australia, environmental messaging about hydrogen[8] had a small but statistically significant effect on support levels; compared to alternative messages about the following: the role of hydrogen blending in the energy transition; the economic benefits of the national hydrogen economy; or policy solutions to make hydrogen energy more affordable for households [86]. In contrast, Damette et al. [70] found that presenting French participants with alternative framings regarding hydrogen's benefits (to the grid, household, or environment) had minimal impact on willingness to choose a hydrogen-based storage system over their current system. However, the study did report novel findings in that participants preferred a different kind of energy system management according to the information framing. Specifically, those informed about environmental benefits were more in favor of the hydrogen system being managed by an energy cooperative, while those aware of household benefits preferred a public management system.

Increased knowledge may result in finer attunement to both the positive and negative aspects of hydrogen applications [83]. When viewed as an environmentally friendly fuel that is suitable for commercial applications [94,228], positive perceptions tend to prevail over safety concerns around hydrogen's explosivity [60,83,228]. Overall, informing the public about hydrogen's historical significance, regulatory status, technical development, and environmental credentials seems to contribute to more positive perceptions (see Table 5), especially when there is a desire to know more about the technology [68].

Table 5
This table reports the impacts of information provision on domestic hydrogen acceptance. The results suggest that positive perceptions of hydrogen are more likely following information provision.

Study	Details of information provision	Results on public perceptions
[42, 75, 87]	• Following the 1990 (2009/142/EC) Gas Appliance Directive (GAD), all appliances manufactured and/or sold in the UK (and EU) since 1993 have been subject to and must pass a short-term test to run on a maximum of 23% hydrogen [42, 75,87] • Prior to natural gas, most UK homes and businesses ran a manufactured mixture called 'town gas'; composed of a mix of methane (CH4), carbon monoxide (CO) and up to 50% hydrogen [42,75,87] • The development of R&D activities [42]	• Greater willingness to participate in community trials for blended hydrogen [42] • Support for hydrogen as a fuel for participants' local areas, for a trial taking place within these areas and for hydrogen as a national fuel scored 6.81, 7.08 and 6.89 out of 10 [87] • Less than 10% of survey participants placed 'no value' on hydrogen [75]
[68]	• A video excerpt of the Leeds City Gate H21 City Gate Project	• Stronger support for domestic hydrogen after viewing the video
[69]	• A new type of domestic gas supply is coming which is unrelated to fracking • This gas will be better for the environment as it has a low carbon footprint • Should the change go ahead, it will apply nationwide regardless of existing energy suppliers • The government will arrive at their decisions within the next 5–10 years	• Respondents previously 'cautious', 'disinterested' or 'unconvinced' about the conversion of natural gas networks and use of hydrogen in their homes were more likely to become 'accepters' of a potential conversion; viewing hydrogen "as an option that needs serious consideration." • Respondents were able to understand and relay basic technical details about the hydrogen conversion in a clear and simple way
[70]	• All participants were provided the same information on hydrogen energy storage, explaining in layman terms why the technology is useful as part of the energy transition and how it can be used in the home	• Participants proved more willing to choose hydrogen-based energy storage systems over the current energy system • Strong positive correlation regarding energy self-sufficiency and support for the proposed hydrogen storage system
[86]	• A video excerpt explaining what hydrogen energy can be used for, how 'green' hydrogen can be produced, and the potential for export markets[a] • Further images and text further explaining a range of hydrogen production methods • Information on how domestic use of hydrogen can reduce emissions, and that trials with up to 20% hydrogen blends have already been trialed in Europe	• Stronger support for domestic hydrogen following information provision • Overall, respondents were slightly to moderately willing to use hydrogen for all domestic purposes (hot water heating, cooking, on-site electricity generation, space heating, blended hydrogen, and HFCVS), with stronger support for hot water heating and cooking
[88]	• A video excerpt on Australia's hydrogen opportunity[b]	• Many participants expressed positive sentiments and agreed that developing a hydrogen industry in Australia seemed like a good idea that could bring economic, energy security, and environmental benefits • Questions were raised about safety, potential costs, local employment opportunities, water scarcity and environmental trade-offs
[89]	• Neutral general information about hydrogen energy technologies, in addition to specific information about the	• Participants considered themselves more likely to accept and support the adoption of

(*continued on next page*)

[7] Manufacturers note that flame visibility is not strictly necessary for heating and hot water appliances due to the sealed combustion chamber and presence of remote flame indication on most boilers, but largely support the requirement for it [67].

[8] "Australia can use its abundant renewable energy resources to produce hydrogen, which will give us 100% emissions-free 'green' energy."

Table 5 (*continued*)

Study	Details of information provision	Results on public perceptions
	consequences of residential fuel cells and HFCVs	residential fuel cells (and HFCVs) all other things being equal
[233]	• Learning assignments in Aalto University, School of Engineering, related to hydrogen safety and small-scale hydrogen production	• Finnish engineering students were more willing to acquire a small-scale domestic hydrogen system once better informed about hydrogen safety

[a] https://www.youtube.com/watch?v=fFGT2z82tOM.
[b] https://www.youtube.com/watch?v=nO63TyoTNxE.

Bogel et al. [76] made an explicit contribution to bridging the knowledge gap on the attitudinal dimensions of hydrogen acceptance, through an assessment of prior perceptions about hydrogen and emergent attitudes following information provision. The study argued that information campaigns based on short and somewhat neutral information may prove a powerful tool at the early stage of technology diffusion, especially when aimed at parts of society with minimal knowledge about hydrogen. By contrast, research on the Polish electromobility market flagged that only 22% of respondents (N = 171) believed that such campaigns would have a positive influence on market deployment and social acceptance of HFCVs, whereas cost reductions and infrastructure development were supported by 90%. Furthermore, Williams et al. [121] found that less than half of respondents felt they understood significantly more about hydrogen boilers or heat pumps after being provided with additional technical information. Martin et al. [86] have also cautioned that factual information may not necessarily increase support levels when strong opposition to hydrogen is preexisting. Notwithstanding, information provision may prove effective when initial attitudes are neutral, or support already exists [76]. Moreover, public engagement with and exposure to HETs may facilitate opportunities for successful market adoption, while also increasing consumer willingness to pay [229] (see Table 6).

4.1.5. Socio-structural factors and hydrogen acceptance

Following Schönauer and Glanz [103], socio-structural factors may prove important to the evolution of hydrogen acceptance. A positive correlation between knowledge and acceptance of hydrogen technologies is noted in the literature [12,227], which typically depends on factors such as higher levels of education, environmental awareness, technology engagement [174], income [99,230], and full-time employment [231]. Notably, Iribarren et al. [94] reported largely positive perceptions of hydrogen's environmental credentials and suitability for Spanish public transportation. The survey study reflected the potential importance of socio-demographic variables to technology acceptance [232], since 72% of respondents were younger than 35 years old and 61% had at least university level education. By contrast, younger Germans were more likely to oppose hydrogen infrastructure on Not-In-My-Back-Yard (NIMBY) grounds, while eldest respondents were the most supportive demographic [103].

Other evidence suggests that older age groups could be somewhat less accepting of HET [12], indicating that the effect of certain socio-demographic factors may prove to be highly place- and context-specific. Researchers in South Korea [99] found that education and income had a positive effect on hydrogen acceptance, while household characteristics also had a significant effect. Irrespective of age, gender, or cultural worldviews,[9] people with limited technical or scientific knowledge may prove less likely to support hydrogen technologies [171]. Tellingly, Bellaby and Upham [231] noted that UK motorists knew more about hydrogen than non-drivers and were more supportive.

In some cases, socio-structural factors may have a weaker influence on acceptance compared to psychological factors [12], especially risk perceptions factors [108]. Notably, Scott and Powells [87] found the relationship between support for hydrogen blending and socio-demographic variables such as age, sex, education, and income to be statistically insignificant. While this finding should not be dismissed outright, it contradicts the wider literature and is yet to be verified in follow-up studies (see Table 7). One explanation could lie with the location of UK survey participants not being verified as part of the study design, while the researchers only screened for a limited selection of socio-demographic characteristics. Additionally, a larger sample size (>N = 742) would provide more reliable data on the statistical significance of socio-demographic variables. In response, a new wave of quantitative research is needed to examine the impact of both information provision and socio-structural variables on domestic hydrogen acceptance.

Table 6
Impacts of public engagement and experience on hydrogen perceptions.

Study	Country	Findings
[100]	Japan	• Familiarity with hydrogen refueling increased acceptance for drivers
[116]	USA	• Experience with HFCVs and refueling stations was mostly positive for a volunteer group of Californian drivers • Responses largely exceeded initial expectations when considering the performance, safety, and practical aspects (N = 54)
[117]	Netherlands	• People living in proximity to a hydrogen fueling station (HFS) were more accepting of this technology following its implementation • Respondents attributed more weight to benefits and less weight to risks than beforehand
[127]	UK	• Following participation in the Hydrogen Bike activity,[a] 88% of respondents previously neutral or with no opinion on hydrogen, now reported a positive feeling

[a] A public exhibit set up to engage participants with a hydrogen bike demonstration and scientific information about hydrogen.

4.2. Barriers to socio-political acceptance

4.2.1. Consumer engagement and trust in the energy transition

Consumer engagement and socio-structural factors may influence

Table 7
This table reports the impact of socio-demographic variables on hydrogen acceptance. The results suggest that age, gender, and education may influence consumer attitudes towards hydrogen, especially regarding safety perceptions.

Study	Findings
[89]	• Male respondents reported a higher level of acceptance relative to female • Those in younger age groups reported a higher level of acceptance
[68]	• Australian women had stronger reservations about the potential disruptive impacts of hydrogen in view of its physical and chemical characteristics, including stronger concerns about hydrogen's odorless nature. • Highly educated respondents were more supportive of using hydrogen for all domestic purposes (i.e. space heating, hot water heating and cooking). • 65% of male respondents either 'very supportive' or 'supportive' of domestic hydrogen, compared to 40% of female respondents.
[83]	• Young, educated males had the most knowledge about hydrogen • Males perceived hydrogen as more explosive and dangerous than females • Older age groups had the strongest perception of hydrogen as unsafe.
[80,174,234]	• Men are more likely to have prior knowledge about hydrogen, making them more inclined to have positive perceptions.

[9] These include trust in technology and environmental awareness, and to a lesser degree (Christian) stewardship for nature and spiritual holism [171].

how the public perceives the costs, benefits, and risks of technology adoption [235], and whether they trust in institutions, actors, and information. At present, widespread consumer disengagement in the energy market remains an obstacle to net zero ambitions and climate change targets (see Table 8). Notably, the UK public remains largely disengaged with developments in the energy market, with around a quarter of consumers yet to switch energy supplier once [181]. According to Ofgem, 54% of consumers remain on expensive default standard variable tariffs (SVTs) [236],[10] while those that switch typically stay the same supplier [237] Citizens most likely to have switched included homeowners and those aged 65 and over [181].

Based on Eurobarometer survey data, Balta-Ozkan and Le Gallo [238] indicated that socio-structural factors may shape trust in institutions, actors, and information. Specifically, gender, income, location, and housing tenure acted as potential determinants of renewable energy acceptance. More years in education, home ownership, and being female contributed positively towards trust in energy companies, whereas energy saving practices and internet access undermined trust levels. Owning a computer and having access to the internet resulted in negative perceptions of fossil fuels and more distrust in utilities as a provider of information, compared to more positive perceptions of RESs and stronger trust in the scientific community, not-for-profit organizations, and the EU. Additionally, homeowners, who have paid or still paying off their mortgages, were also more likely to trust in supra-national, national, and sub-national government [238].

Table 8
This table summarizes findings on public perceptions of the energy sector and energy transition. The results show that greater levels of public trust are needed to support the transition.

Study	Findings
[69]	• Limited engagement with the energy sector beyond switching energy supplier
[70]	• Consumers expressed weak preferences for hydrogen homes to be managed by private companies, placing more trust in energy cooperatives and municipalities
[122]	• Mistrust over the issue of 'green taxes', which some see as a political ploy to extract more tax revenues without a real commitment to addressing environmental problems
[144]	• In terms of financing the UK energy transition, respondents assigned most responsibility to energy companies (45%), followed by government (32%), the public (12%), and future residents (11%)
[239]	• Deep rooted public mistrust of electricity companies • Trustworthiness and popularity of community energy schemes
[238]	• Residents in large urban areas[a] had greater trust in government and political entities than rural residents • Both large and small city residents were more trusting in the EU, scientists, environmental protection agencies, and journalists than their rural counterparts
[240]	• Consumers regard the transactions of energy companies as opaque, leading to distrust and suspicion, especially when prices rise despite technological advancements
[241]	• Mistrust is more common in communities disengaged from actively managing their energy choices and consumption costs
[242]	• The credibility of promoted energy savings schemes is undermined when consumers perceive power companies as deriving profits from increased energy consumption
[243]	• The public considers energy companies as accountable for helping to lead the transition, but view their contribution to date as insufficient, especially given their ability to invest sizeable capital in low-carbon energy infrastructure and technologies Conditions for establishing public trust are especially challenging when energy companies are primarily perceived as "profit-making entities"

[a] The terms large cities, large urban areas, and large urban communities were used interchangeably.

[10] The difference between the average SVT price of the six large suppliers and the cheapest market tariff was on average £320 between June 2017 and June 2018 [236].

4.2.2. Public trust in the hydrogen transition

Early hydrogen acceptance studies conducted in the UK [79,81,172] suggested mixed reports concerning public trust levels in institutions, actors, and information, as well as perceptions of safety issues, risk management, and trust. Based on findings from the final survey phase of the BP-Imperial College (BP-IC) Hydrogen acceptance project (2004–2007), O'Garra [172] reported a wide discrepancy between consumer trust levels according to the information provider. It was noted that perceptions remained fixed throughout the study period, indicating that trust may be hard fought and somewhat static.

More recently, in the context of the HyDeploy demonstration project,[11] the underlying motives of the central government were viewed with skepticism [87]. Due to past policy failures and inconsistent messages regarding energy technologies such as the promotion of diesel cars and solar panels [122], the UK public may see the central government as a credible authority in some respects, but also feel distrust and suspicion [42]. This is reflected by a perceived lack of trust in key decisions makers and the overall system of governance, which may stifle stakeholder inclusion and participatory processes at the community level [123]. The credibility of the UK government may be further undermined due to failure to lead by example on the part of elected officials [42].

Overall, the evidence base underscores an apparent rift between public perceptions of intentions and actions regarding the government, industry, and business (see Table 9). The public appears willing to trust the government and gas companies to manage safety challenges and risk factors, while remaining skeptical about the commitment of these entities to procedural justice.

Trust levels and related attitudes towards key actors may also vary significantly between communities and according to socio-structural factors. For example, younger demographics in Australia were less willing to trust the government and expressed a preference for community-based projects, while older participants flagged their concerns over how urban areas have been given preferential treatment at the expense of regional communities [88]. Elsewhere, the DGA [122] reported a divergence between respondents in the North and South of England, especially regarding safety perceptions, which appears to reflect a wider rift in terms of socio-political acceptance. Southerners were more cynical about the motives of businesses and skeptical about hydrogen delivering energy efficiency improvements to industry or business, whereas northerners were enthusiastic about these prospects, which could be attributed to a greater sense of pro-hydrogen 'place attachment' [244] and 'place-technology fit' [137] linked to the north's industrial heritage.[12]

4.2.3. Hydrogen production pathways

At present, around 95% of global hydrogen production is sourced from fossil fuels, which includes 48% via steam methane reformation (SMR), 30% from petroleum fraction, and 18% from coal gasification [245]. SMR is dependent on large quantities of natural gas [246], making it environmentally contentious [247] and highly cost-intensive [248]; nevertheless, it remains the most technically feasible and economical method for delivering large-scale hydrogen production [246,247,249]. Electrolysis – the process of electrochemically converting water into hydrogen and oxygen using renewable electrical energy [250] – accounts for around 4% of global hydrogen production [245]. Electrolysis is increasingly considered as an alternative pathway to achieving large-scale hydrogen production with a lower carbon

[11] Launched on Keele University's private gas network to test the safety case for hydrogen blending.

[12] A locality characterized by a history of socio-economic deprivation and unemployment, as well as a legacy of pollution and environmental degradation due to the presence of heavy industry.

Table 9
This table summarizes findings on public trust in the hydrogen transition. The results show the extent to which trust levels may vary according to actor or stakeholder.

Study	Country	Findings
[68]	Australia	• High trust in government, moderate trust in research organizations, and low levels of trust in the media to disseminate information
[68,86]	Australia	• Research institutions as the most trustworthy entity for acting in the public's interest, followed by environmental non-government organizations (ENGOs)
[68,86,87]	UK, Australia	• Skepticism about the motives of fuel/gas and electricity generation companies
[68,87,123]	UK, Australia	• Strong public trust in gas companies and the government to uphold stringent safety standards for hydrogen gas and manage environmental risks competently
[79]	UK	• Opposition to hydrogen storage and refueling facilities in London was strongly associated with inadequate trust in safety regulations, as well as non-environmental attitudes
[87]	UK	• Local Members of Parliament (MPs), and the media considered as untrustworthy sources of information concerning hydrogen • Public trust was highest in evidence provided by the Health and Safety Executive (HSE), followed by universities
[179]	UK	• Low risks levels associated with hydrogen technologies due to underlying trust in safety processes and measures.
[172]	UK	• Stronger trust in information sourced from universities, the BBC, and environmental organizations • Oil companies and car companies considered the least trustworthy
[103]	Germany	• Higher trust in scientific stakeholders resulted in less NIMBY opposition to hydrogen infrastructure • Higher trust in civic stakeholders increased NIMBY opposition Trust in political stakeholders led to more community acceptance but also more ambivalence
[117]	Netherlands	• Trust in industry had a positive effect on feelings of pride and joy, and a corresponding negative effect on fear for citizens living in proximity to a HFS
[122]	UK	• Neutral trust in regulators such as the Office of gas and electricity markets (Ofgem)
[123]	UK	• Uncertainty about whether the national government, local councils, and local businesses can be trusted to make good decisions about hydrogen technologies

footprint [251].

The legitimacy of this alternative is well reflected by a divergence in the recent literature on 'socio-technical-economic' aspects of hydrogen production and deployment [252]. Studies published between 2008 and 2012 concluded that SMR-based hydrogen production would be the lowest-cost method over the long-term, whereas subsequent studies (2013–2017) contend that electrolytic hydrogen can become cost competitive [252]. This argument follows the higher penetration of RESs into the electricity grid [252], and the prospect of further declining costs for renewables [253] including wind and solar power [54]. Furthermore, there is significant potential to scale up renewable hydrogen sourced from curtailed electricity [254–256]. Given hydrogen's advantage as a power storage medium, this could enable more efficient electricity grid management [255,257]. Considering the high capital loss of wind energy, converting curtailed energy into hydrogen may prove more economical than extending the UK electricity network [258]. Consequently, offshore wind farms (OWFs) may present the best investment opportunity for achieving a hybrid energy system using Power-to-Gas (PtG) sourced from electrolytic hydrogen [259].

In effect, the global hydrogen landscape is evolving to include a range of industrial, commercial, and domestic applications centered on a combination of large volumes of carbon capture, utilization and storage (CCUS-) enabled ('blue') and electrolytic ('green') hydrogen [260]. Since green hydrogen faces a scarcity challenge in the near-to medium-term which may prevent economies of scale, blue hydrogen could play an enabling role in supporting "the uptake of hydrogen infrastructure and hydrogen end-use transformation" [261].

As envisioned in the UK Hydrogen Strategy, this 'twin track' approach is designed to help 'future-proof' the country's net zero ambitions by avoiding over reliance on a single technology pathway [18]. The strategy builds off the target for 5 GW of low-carbon hydrogen production capacity economy-wide by 2030, as set out in the Ten Point Plan for a Green Industrial Revolution [262].[13] The evolution of mixed production pathways for hydrogen over the short-, medium- and long-term is further reflected in Points 1 and 8 of the UK government's Ten Point Plan, aiming to achieve a four-fold increase in offshore wind capacity by 2030, and capture of 10 Mt of carbon dioxide (CO_2) by 2030 through the £1 billion CCUS Infrastructure [262].

4.2.4. Environmental impacts

Hydrogen's environmental impacts are a matter of growing controversy in the scientific community [263]. Although hydrogen is by most measures a clean energy vector with a critical role to play in decarbonization, its potential adverse climate change and environmental impacts remain underexplored by atmospheric scientists and the wider scientific community [264]. The climate change credentials of blue hydrogen rest on at least two key parameters linked to greenhouse gas (GHG) emissions. Firstly, the global warming potential (GWP) of CH_4 is around 25–28 times higher than that of CO_2 over a 100-year time horizon [265], signaling the importance of upstream CH_4 emissions for a net zero transition [261]. Secondly, and equally applicable for green hydrogen, the GWP of nitrous oxide (N_2O) is around 300 times that of CO_2 [266]. Discussing the downstream consequences of hydrogen boilers, Lewis [267,268] has further warned that potential NO_X emissions from hydrogen boilers may fall disproportionately among disadvantaged communities and low-income households. In the UK, this point is especially pertinent given that domestic hydrogen transition will begin with industrial towns in the North of England [154,269].

The climate change impacts of hydrogen have also been examined from a life cycle assessment (LCA) perspective [261,270,271]. If blue hydrogen production is to prove compatible with climate change mitigation, CH_4 emissions rates of the natural gas supply chain must be kept below 0.5% and combined with higher CO_2 capture rates above 95% [261].[14] In the case of green hydrogen, the carbon intensity of the electricity grid should be below 70 kgCO2,eq/MWh to be comparable to the best blue hydrogen production practices [272]. Other environmental impacts include particulate matter formation, terrestrial acidification, mineral resource depletion, and freshwater ecotoxicity [272].

4.2.5. Public perceptions of hydrogen production and environmental impacts

Hydrogen can be produced by various means [18], however, evidence on public perceptions of production pathways remains largely limited to highly developed economies, with an underlying focus on blue and/or green production (see Table 10). In the case of hydrogen produced via nuclear power, social acceptance issues may persist due to negative safety perceptions in the public sphere [39]. Even for a leading nuclear power producer such as South Korea, public perceptions may be highly polarized [230].

Despite the controversy surrounding the idea of blue hydrogen as a bridging technology to renewable-based production methods [261,273], few studies have examined whether the public may tolerate the idea of

[13] Estimated to be equivalent to the amount of gas consumed by over 3 million households each year.

[14] Exhibiting a life cycle GHG footprint of not more than 2–3.5 kg CO_2- eq./kg [261].

Table 10
This table reports on public perceptions of hydrogen production methods and environmental impacts. Results indicate stronger support for hydrogen produced from renewable energy sources.

Source	Findings
[50]	• In Pakistan, biomass and solar energy ranked as more acceptable sources of hydrogen production than wind, municipal solid waste (MSW), and geothermal
[42,121]	• Dual-fuel appliances may require natural gas to act as a backup power source could prove contentious due to environmental impacts
[68,86,88]	• Strong support in Australia for hydrogen's promise as a potential solution for environmental and energy challenges
[75]	• 70% of UK respondents believed hydrogen fuel would have positive impacts on the environment
[76]	• Most EU citizens considered hydrogen to be a good or very good solution for energy and environmental challenges • Agreement levels increased from 75% to 84%–92% according to level of familiarity with the technology (*slightly familiar, familiar, very familiar*)
[86,128, 129]	• Respondents in Australia, Germany, and the Republic of Ireland perceived water scarcity as a risk factor for electrolysis-based hydrogen
[88]	• 74% of Australian respondents were in favor of renewable-based hydrogen production and believed it would help protect the environment • Only 24% backed CCS as a long-term option while 54% accepted blue hydrogen as a transitional fuel
[123]	• UK respondents preferred green and blue hydrogen to natural gas, with mean scores of 82/100 and 59/100 • Natural gas was somewhat preferred to brown hydrogen, scoring 32/100
[128]	• All participants in the Republic of Ireland preferred green hydrogen, with limited tolerance for other production methods.
[230]	• 40% of South Koreans accepted hydrogen produced from nuclear power, 40% were neutral, and 20% were in opposition
[231]	• Stronger public support for renewable-based hydrogen generation than fossil-fuel or nuclear-based production methods. However, CCS did not feature as a technology option in this UK opinion poll
[275]	• Social awareness of wind energy in Iran is associated with higher acceptance of wind turbines as a hydrogen generating source

an enabling role for SMR and CCS in the hydrogen transition [274]. When considering Australia's energy future, the public expressed similar, albeit slightly lower support levels for hydrogen compared to wind and solar power, which eclipsed support for nuclear power or fossil fuels [86]. Interestingly, there was stronger belief that hydrogen should be sourced solely from renewables [86] compared to previous studies [68,88]. Non-renewable based production methods may present a barrier to acceptance, especially among more environmentally conscious parts of the public [68,231]. Notwithstanding, the public appears to recognize that the timeframes for producing renewable hydrogen at scale remain uncertain [69].

For the most past, social acceptance has been gauged through results from public surveys and focus groups. Some researchers have employed alternative methods such as structural equation modeling (SEM) [275], or a two-stage fuzzy multi-criteria decision-making (MCDM) approach [50]. However, studies relying strictly on computational methods may lack validity when it comes to assessing social acceptance at a community or individual level.

Acknowledging the contested policy space surrounding hydrogen and electrification [123], Damette et al. [70] provided a more nuanced analysis of public perceptions of decarbonization pathways regarding hydrogen homes. The study analyzed three scenarios in the French context: (1) hydrogen is converted into electricity off-site and then supplied to households using existing electricity transmission networks (power-to-gas-to-power); (2) hydrogen gas blended with natural gas (PtG) is supplied and used as a fuel in boilers to create heat; (3) hydrogen gas is supplied directly to the residence and can be transformed into heat and electricity by a co-generation boiler. A principal finding was that consumer preferences may depend on familiarity levels with different energy carriers. Overall, consumers preferred the first option compared to the gas-based alternatives, which was especially true for households relying solely on electricity. Furthermore, French gas users proved largely indifferent to these supply methods, which contradicts evidence in the UK [123]. A possible explanation could lie with distinct energy cultures, namely a well-established gas culture in the UK [276], compared to a high penetration of nuclear power in French electricity generation [277].

4.3. Barriers to market acceptance

4.3.1. Economic factors through the UK lens

The net economic impacts of hydrogen are strongly influenced by its cost-competitiveness [18]. For blue hydrogen, this will depend on how the price of hydrogen compares to natural gas [68], among other factors such as CH_4 leakage rates and the costs of CO_2 storage [261]. More broadly, the energy trilemma – defined by problems arising from economic (energy finance), politics (energy security), and the environment (climate change mitigation) [278] – presents a growing problem to countries such as the UK [279]. These factors strongly impact public perceptions of energy policy and emerging technologies such as hydrogen. Notably, in response to recent market volatility[15] – arising from growing geopolitical tensions, economic instability, and a series of unfavorable local and global weather patterns [280], which met the worst of conceivable risk scenarios [281] – Ofgem increased the energy price cap by £139 to £1,277 [282]. Following October 1, 2021, this change directly impacted approximately 15 million people nationwide [283].[16]

The public faces a time of growing uncertainty when it comes to energy costs, which raises consumer expectations for reduced energy bills once natural gas is replaced by low-carbon energy sources. However, consumer research led by the UK's largest Gas Distribution Network Operator (GDNO), Cadent Gas, suggests that most households incorrectly associate a switch to a low-carbon hot water and heating solution with lower long-term running costs [284].[17] In addition to cost-competitiveness and security of supply factors [280,285,286], market acceptance will depend on how socio-economic benefits are delivered through regional development and employment opportunities, as part of the UK's industrial strategy [287,288]. Notably, there is significant potential for industrial symbiosis and hydrogen hubs, which could bring regional economic benefits [123]. In this respect, lessons can be learned from the missed opportunity of developing local supply chains around the offshore wind industry [123,289].

4.3.2. Public perceptions of economic impacts

Evidence suggests that the UK public may regard the impact of domestic hydrogen on the national economy to be either neutral or positive [75]. One study found that approximately three-quarters of online survey respondents perceived that there would be 'no impact' on the economy, while nearly one-quarter saw a potential 'positive impact' [75]. For respondents who took the paper survey, there was an approximate 60-40 split between neutral and positive perceptions. In contrast, the Australian public had mostly positive perceptions about the hydrogen transition creating new jobs and opportunities for skills acquisition [68]. This discrepancy between national contexts could be because the ARENA study examined perceptions and attitudes towards

[15] The UK natural gas price peaked at around 290 pence per therm in October 2021, compared to an annual low of 36 pence per therm in March [325].
[16] Ofgem reviews and sets the energy price cap twice a year to limit how much suppliers can charge domestic customers for gas and electricity, applying to customers on default (SVTs) tariffs [282,283].
[17] This finding was reported in Cadent's Triangulation report – *Developing a Greenprint for Gas: Customer Preference Research* – which is due for publication in 2022 as a follow up to Ref. [284].

hydrogen in the transport sector, for domestic use and moreover, as an export commodity [68], whereas Scott and Powells [75] looked solely at hydrogen as a fuel for UK homes.

Importantly, consumers want to see community benefits prioritized, whereby the economic benefits of new jobs can support future generations [88]. This especially means safeguarding against the risk of a 'boom and bust' cycle around emergent hydrogen hubs [88]. In response, researchers should target a deeper understanding of how the public perceives the prospect of socio-economic benefits being delivered through projects such as HyNet North West, which exemplifies the drive to develop regional hydrogen hubs in proximity to industrial clusters [290]. Interestingly, existing industrial structure may also increase consumer acceptance towards hydrogen technologies, specifically HFCVs [114]. Data collected in China (Jiangsu Province) suggested that cooperation between industries and manufacturers promotes public trust in industrial agglomeration around the hydrogen economy [114].

To date, few studies have compared consumer preferences for hydrogen applications, while limited public feedback is available on national hydrogen strategies. In Germany, 65% of survey respondents (N = 512) rated the use of hydrogen as an energy carrier (e.g. for heat, in transport, or in industry) as 'very positive' or 'positive' [103]. Interestingly, consumer acceptance in Leeds proved highest for public transport applications, based on a mean score of 80/100, compared to 75 for vehicles, 71 for refueling stations, and 69 for heating [123]. However, these results predate the publication of national hydrogen strategies. Follow-up studies are needed to better gauge how social acceptance for domestic hydrogen may interact with, or even depend on, public response to other hydrogen applications.

4.3.3. Technology choice

By choosing between hydrogen boilers and other low-carbon heating solutions [138], which implies supporting different production pathways, households will play a key role in determining the evolution of national gas infrastructure networks and electricity grids [68]. As discussed in section 4.1.1, hydrogen acceptance is likely to hinge on how its technical complexity and unfamiliarity compare to other low-carbon technologies for domestic heating and cooking [121]. Additionally, technology choice could determine the public's willingness to adopt hydrogen energy technologies [89], which may depend on perceptions of substitutability [138]. Substitutability has proven to be a prerequisite for securing social acceptance in the case of electricity sources such as nuclear power [291,292] and may prove equally critical to how the public chooses between hydrogen appliances and competing technologies [138].

Compared to alternatives such as heat pumps and district heating [138], the public seems to perceive hydrogen as more of a direct substitute for natural gas, since it would be supplied to households in a similar way following structural changes to the national gas grid [121]. In terms of technology preference, the DGA [122] found that support levels were highest for blending hydrogen and biomethane into the grid, followed by converting home heating to hydrogen. A hybrid heating system – combining an electric heat pump and an existing gas boiler – also proved more popular than heat pumps.

The UK public appear to view heat pumps as a subpar substitute for natural gas boilers due to greater spatial requirements, and potentially disruptive and inconvenient performance characteristics [122]. However, following information provision, Williams et al. [121] reported that 45–55% of respondents had no clear preference towards either hydrogen heating or heat pumps. This observation raises further questions about the public's technical understanding of low-carbon heating solutions. Nevertheless, should the hydrogen economy succeed in increasing overall market choice for low-carbon energy technologies, consumers may prove more in favor of the transition [115].

Decisions to adopt hydrogen home appliances may also depend on customer loyalty to their current boiler manufacturer. This factor could become highly influential, given that market leaders Worcester Bosch and Baxi Heating are key actors in the UK's hydrogen trials [293,327]; having developed prototype hydrogen boilers for the Hy4Heat programme [19]. Two of the other 'big four' boiler manufacturers have also committed to selling a new generation of 'hydrogen-ready' boilers at a similar point to natural gas systems on a volume basis [294,295].

Lambert and Ashworth [68] obeserved that younger and higher educated Australians expressed more support for electrification. All-electric households were less supportive of the use of any hydrogen in the gas network, whereas support for hydrogen was higher in urban areas and locations with frequent power outages. It should also be noted that households relying on or intending to use electric cookers or heat pumps may prefer to have no connection to the gas grid [121]. Regarding gas preferences, Ashworth et al. [88] found that 67% of participants preferred hydrogen, while 26% were undecided and only 7% chose to remain with natural gas. Based on this finding, there may be a prevailing tendency for consumers to support hydrogen when choosing strictly between gas-based heating and cooking, as opposed to electric or other alternatives.

First steps have been taken to gauge the public's perceptions of hydrogen appliances, including those running on a blend of up to 20% hydrogen, compared to other low-carbon alternatives such as heat pumps. Overall, the public appears receptive to the idea of hydrogen blending as a non-disruptive or potentially positive technology, suited to preserving the lived experience of heating and cooking with natural gas [75]. However, there is sparse evidence on public perceptions of a full-scale conversion to domestic hydrogen use, as opposed to hydrogen blending which has been promoted as a practical, safe, and viable interim decarbonization pathway [60]. More research is needed to determine if a full-scale conversion to hydrogen homes will be viewed comparably, while understanding the reasons why the public may hold certain views towards alternative technology options for domestic heating and cooking. Given the dynamic and hybrid nature of the low-carbon transition, researchers should aim to understand whether these options are seen as competing or complementary decarbonization pathways in the eyes of the public.

4.3.4. Boiler replacement trends and socio-economic factors

Reviewing the uptake of seven energy efficient heating systems, Ipsos MORI and the Energy Saving Trust [296] found that 30% of respondents cited system breakdown as the main reason for replacing their heating system, while 36% had never done so and 19% anticipated waiting more than 20 years to do so. These results reflect the fact that 1.67 million gas boilers were sold in the UK in 2019 [297], representing around 7% of homes connected to the gas grid [298].[18] Importantly, system breakdown is the most common trigger for homeowners to consider replacing their heating system [296]. However, a large proportion of the UK housing stock has never undertaken such a replacement and moreover, expects this to happen around once every fifteen years [296].

Assuming that the average life of a boiler is approximately 12 years, a high percentage of households may be several years away from changing their boiler unless there is a direct incentive in place [67]. Consequently, consumers will be more hesitant to make a system change having recently bought a new boiler, especially when this includes an upfront service plan [42]. Consumers could therefore reject the switchover if worries over financial losses amount to a feeling of technology lock in, following a recent purchase or modification [42]. Overall, consumers appear more willing to adopt low-carbon heating systems when their existing gas boiler needs replacement, with cost being the key factor behind this decision [121,296,299].

People with low incomes or savings are less likely to have previously replaced their heating system and expect to do so with less frequency

[18] It is estimated that the number of UK homes with a gas connection increased from around 7.7 million in 1970 to around 23.3 million in 2011 [326].

than higher-income earners [296]. Additionally, low-income groups are less likely to install a more efficient heating system than higher-income groups [296]. These findings are unsurprising since inability to afford new technologies falls disproportionately upon low-income earners [300,301], making fuel cost a more significant factor to this demographic group [68]. Dorrington et al. [67] highlight further reluctance on the part of consumers, given that appliances rolled-out during the early stages of the transition may have relatively shorter lifespans than current natural gas appliances or future hydrogen appliances. Notably, hydrogen's flame characteristics may decrease the lifetime durability of appliances, calling for more frequent and modified maintenance measures, which may dissuade consumers if there is a perceived lack of trained engineers and skilled technicians [42].

4.3.5. Hydrogen cost factors

At the micro-scale, market acceptance is shaped by the extent to which consumers are forced to absorb costs of the hydrogen transition, largely stemming from high production costs [248]. This could materialize through higher taxes and/or energy bills levied nationwide, in addition to purchases made for new appliances or smaller payments to modify existing natural gas appliances [72,75]. Burke and Rooney [302] estimate the total costs of converting gas appliances to hydrogen to be around £3,000 per home, which is still much less capital-intensive than most alternative low-carbon technologies such as heat pumps. While annual running costs vary marginally, the total installation costs of air source heat pumps (ASHPs) have been estimated to range between £5–10 k [302], £5–8 k [303], or £7–13 k [304], while ground source heat pumps (GSHPs) range between £10–15 k [302], £11–15 k, or £14–19 k [304], according to house size and area [303].

The UK Government recently announced a £450 million Boiler Upgrade Scheme to support households with grants of £5,000 or £6,000 when making the switch to an ASHP or GSHP [19]. However, this level of funding amounts to a potential switchover for approximately 30,000 homes over a three-year period, which pales in comparison to the current target for 600,000 heat pump installations per year by 2028, as part of the *Greener buildings* objective [262].[19] Consequently, hydrogen boilers would present a more attractive purchasing option for low-income households, as well as other consumers unable to invest in high up-front costs. Furthermore, it is anticipated that the market price of hydrogen boilers could be equivalent to natural gas boilers by 2030 [305].

4.3.6. Public perceptions of financial costs

In the context of a hydrogen heating community trial, Grey et al. [42] identified a range of potential barriers to market acceptance for potential early adopters, such as costs and disruptive impacts, which can be extrapolated to the switchover and wider transition. The study reported that UK consumers want to feel confident about the stated or promised savings being fulfilled, placing high importance on investment, operational and lifetime costs, energy prices and tariff structure. Consumers are especially concerned about purchase costs since a switchover to domestic hydrogen is likely to require personal (financial) investments in new appliances [68,87], which the public expect to be subsidized [123]. Such expectations are mirrored internationally, with 95% of Taiwanese respondents calling a government subsidy of at least 22% to support the purchase of hydrogen-electric motorcycles [304]. Similarly, most Polish users of hybrid and electric vehicles (91%; N = 171) regarded financial and fiscal incentives as having the most positive impact on willingness to purchase HFCVs.

UK respondents view low energy bills, and purchase and running costs, as the most important factors of new heating systems, attributing less importance to functionality, efficiency, reliability, or aesthetics: 24% and 23% of respondents cited low energy bills and low running costs as the most important criteria; 10% regarded capital costs as an important factor; and 5% prioritized cheap purchase and installation [296]. As has been the case for renewable electricity [140], it is apparent that willingness to pay for low-carbon technologies such as hydrogen will depend on socio-structural factors [306]. According to Wave 37 of the Department for Business, Energy & Industrial Strategy (BEIS) public attitude tracker (March 2021), 29% and 11% of the public were 'fairly worried' and 'very worried' about paying for energy bills, which marked a 3% increase from the previous year [181]. The most worried demographic group were those aged 25 to 34 in social grades C2DE, while private and social renters expressed higher concerns about energy costs than owner occupiers. Scott and Powells [75] also found that hydrogen affordability presented the greatest barrier to social acceptance for survey participants in a region characterized by socio-economic deprivation and a legacy of industrial and economic stagnation.

Evidence from Australia and the Netherlands largely confirms that cost considerations are a priority (see Table 11). Beyond these findings and recent insights on consumer perceptions of hydrogen costs in the context of the HyDeploy [87] and H21 projects [69], there is little concrete evidence of the public's willingness to pay for domestic hydrogen. Whether consumers actively or passively accept hydrogen in their homes [153], the public should be willing to pay for new appliances, otherwise a transition is unlikely to take place without government mandates [284]. A case in point is the UK transition from 'town' gas to natural gas (1960–1977) [307], which took place during a command and control economy [302].

4.4. Barriers to community acceptance

4.4.1. Spatial dynamics of hydrogen communities in the UK

At present, it remains unclear how the transition to domestic hydrogen should be managed to account for socio-economic differences across the housing stock and problems of fuel poverty [75]. Confronting this knowledge gap is especially pertinent in the UK context, since the first wave of hydrogen projects will be deployed across industrial cities characterized by disparate economic and social geographies [69,75].

Table 11
This table provides evidence on public perceptions of hydrogen cost factors. Given mixed reports in the literature, cost concerns and barriers may prove place-specific and context dependent.

Study	Findings
[68]	• High levels of public support for developing Australia's hydrogen economy rested on the promise that regional industrial projects would deliver cost-competitive prices to consumers
[69]	• Relatively low levels of concern among UK survey participants given the scenario that hydrogen resulted in an estimated 7% increase to their gas bill • Concerns were still raised about the need to invest in new appliances for heating and cooking
[75]	• Grievances over high energy bills and low wages rendered around two-thirds of UK respondents as unable to absorb potentially higher prices for hydrogen, even if they expressed willingness to pay more for it
[83]	• 67% of Dutch respondents would be willing to use blended hydrogen if the switchover required a one-time changeover cost of €100 • 45% of respondents supported the use of blended hydrogen provided its running costs did not exceed those of natural gas by more than 10%
[86]	• French consumers were prepared to pay €100–136 to be more self-sufficient via stationary hydrogen-based storage systems, but they were not prepared to pay more for other attributes related to this switch
[87]	• Costs presented the main barrier to consumer support for hydrogen, with 77% of UK respondents unable and/or unwilling to pay higher energy bills
[88]	• Limited willingness to pay more for gas bills in Australia, with strong financial pressures already straining most household budgets
[123]	• For every £100 currently spent on home heating, people facing financial hardship were prepare and those financially secure were prepared to pay £102 and £111 for hydrogen (the mean response was £108)
[128]	• Participants indicated that increased long-term costs would lead to a comprehensive rejection of a transition to hydrogen

[19] Point 7 in the Ten Point Plan for a Green Industrial Revolution [262].

While GDNOs are strategically targeting these locations due to their competitive advantage for converting to hydrogen homes [153], this deployment trajectory raises governance challenges concerning consumer choice and rights [302].

The spatial dynamics of the UK hydrogen conversion – characterized by a notable degree of exclusivity given that around four million households (~15%) are located off-grid [308] and targeted deployment in proximity to industrial clusters [269] – amplifies the challenge of securing distributional justice. Taking the example H21 Leeds City Gate project, the capital cost of converting the gas network to hydrogen was estimated at £2.05 billion, with an annual operational cost of £139 million [302]. It was calculated this would result in an increase of around 1% to all consumer bills if the costs were shared nationwide [302]. It has also been shown that the estimated costs of decarbonizing the Welsh housing sector vary significantly according to tenure and status [309]. Average investment required per home ranging from £35, 984 for fuel poor housing and £24,000 for social housing, to £4,700 for the private rented sector and £4,525 for owner occupiers [309]. Moreover, socially disadvantaged households lack opportunities to improve the envelope of their building and remain limited in their choice about energy technologies [72].

In addition to the issue of "equality of access to, and resultant efficiency of infrastructure, in the context of both location and housing type" [72], consumers may face practical and economic challenges should they wish to opt out of adopting hydrogen following a unilateral network switch [302]. If this option proves unviable it may contribute to a lack of equity between communities. The geographical nature of the roll-out could exacerbate issues of fuel poverty, especially if households excluded from the hydrogen transition are left facing higher energy bills [302]. From an energy equity perspective, private renters may face being locked into decisions made by landlords, while off-grid, rural communities could be doubly excluded from the energy transition since they may lack access to hydrogen networks or electrification [72]. This risk has been stressed by the Scottish Government, given that the combination of living off-grid and in a hard-to-treat property is an amplifier of fuel poverty, which means future heating solutions in Scotland need to be rural-proofed [310,311].

4.4.2. Public perceptions of community acceptance

Hydrogen acceptance could prove highly place-specific, whether at the country, regional, or local scale [123]. In Japan, consumer confidence and social acceptability increased for residents with a HFS in their local area [104]. In contrast, acceptance levels were lower for Germans for hydrogen infrastructure implemented in their neighborhood, highlighting the potential for NIMBY opposition [103]. However, Damette et al. [70] failed to find a significant effect for consumer opposition in relation to hydrogen energy storage systems being implemented at the neighborhood level in France. Martin et al. [86] observed that Australians were more willing to support a hydrogen production facility in their local area if dedicated to domestic use rather than for export, regardless of location or area type. Citizens of Leeds also expressed moderate to high levels of acceptance for hydrogen as a stimulus for developing a local green economy [123]; supporting the notion that local industries should be set up to produce hydrogen with local people support these developments.

Decisions regarding the distribution of costs could prove decisive to whether the hydrogen transition materializes in a socially acceptable way. Scholars have flagged the need to address how the costs of domestic hydrogen can be socialized equitably, while the transition is governed in a way that accounts for potential conflicts regarding consumer choice and rights [72,75,302]. Examining emotional responses to the first HFS in the Netherlands, Hujits [117] reported a stronger feeling of anger when higher levels of procedural and distributional injustice were perceived by citizens. Perceived unfairness also gave rise to feelings of fear, as did concerns around safety and risk which were heightened by a lack of prior awareness of the HFS. However, few studies have examined aspects of energy justice linked to the hydrogen switchover such as the distribution of costs [75] and potential impacts on vulnerable households [72].

Addressing energy vulnerabilities, Scott and Powells [87] highlighted public concern about the prospect of low-income households becoming further disenfranchised if hydrogen leads to higher energy costs. Consumers appear somewhat attuned to the importance of accounting for households with vulnerable or immobile occupants, while also acknowledging that appliances should be adapted for those with special needs [42,69]. When presented with a hypothetical hydrogen trial for around 300 homes, focus group participants raised concerns about the welfare of vulnerable members of the community such as the elderly and young, and those with health conditions or disabilities [42]. Worries were heightened for the switchover period, which could see households disconnected from the gas grid for up to two weeks.[20] Even if the switchover took place during the summer months, respondents stressed this would not offset the need for heating and hot water.[21] Split perspectives have also been reported, with 39% of respondents unconcerned about being disconnected from the gas grid for a few days, compared to 34% expressing concern [122]. Interestingly, Fylan et al. [69] noted that survey respondents assumed that the period of disconnection from the gas grid might be a few hours, as opposed to several days.

4.5. Barriers to behavioral acceptance

4.5.1. Public perceptions of the lived experience of heating and cooking

As a domestic energy technology, hydrogen will bring new experience and meaning into the daily practices of heating and cooking [75]; reflecting the notion that human activity revolves around a "shared practical understanding" that is 'embodied' and 'mediated' by surrounding 'materialities' [312]. Such activities will form "part of the ongoing reproduction of bundles and complexes of social practice" that shape the energy transition [165], with this 'material participation' offering a mechanism to cultivate the kind of 'energy citizenship' needed to accelerate the uptake of low-carbon technologies [123,313]. This focus reflects how the expediency of daily life may underpin hydrogen acceptance across different social geographies [178].

To date, there has been little public engagement with hydrogen homes in terms of testing appliances. Consequently, there is limited evidence on behavioral barriers compared to other acceptance dimensions, with researchers relying on survey results from hypothetical scenarios. Adopting a social practice approach, Scott and Powells [60] provided participants with simple pieces of information regarding the material and socio-technical properties of hydrogen and asked how these properties might impact their existing hob and boiler practices. The study found that 60% of participants would be 'slightly less comfortable' or 'much less comfortable' using hydrogen for their heating and cooking activities, while only 20% of participants believed 'it would make no difference'. This finding is noteworthy since same authors previously reported that UK consumers perceived the potential impacts on their use of appliances and the lived experience of heating and cooking to be negligible [87]. The above viewpoint was echoed by Australians [68] based on the understanding that hydrogen gas is expected to provide a fast, quiet and unintrusive domestic heating system that provides a close substitute for natural gas [121]; causing minimal disruption to consumer habits compared to alternatives such as heat pumps [314].

[20] The welfare of pets was also raised as a concern.

[21] A potential technical solution to reduce conversion times could be designing new hydrogen boilers to share a common backplate with existing natural gas boilers [67].

4.5.2. Divergence in public perceptions of hydrogen heating and cooking

Closer examination suggests that consumers are more likely to reject changes to hob practices, which may result in divergent decarbonization pathways for cooking and heating [60]. This could be attributable to the contrasting 'socio-material nature' of the two activities. Boiler practices (heating and hot water) are typically seen as 'detached', 'invisible' and 'backgrounded', whereas cooking is a distinctly 'intimate', 'visible' and 'foregrounded' activity, which makes kitchen activities more susceptible to disruptions and safety complications [60]. Consequently, 42% of participants believed hydrogen would bring no change at all to their heating practices, compared to 13% expecting a 'significant' or 'complete' change, whereas 30% of respondents anticipated 'significant' or 'complete' change to their cooking practices.

Based on these findings, it is apparent that failure to adequately account for implications related to the lived experience of hydrogen homes, characterized by a potential divergence between heating and cooking practices, would significantly hamper the efficacy of the domestic hydrogen transition. Nonetheless, it should be borne in mind that gas may be the preferred cooking fuel depending on national and cultural context [86]. Overall, consumers are mainly concerned that a switch to hydrogen appliances will deliver the same heating and cooking experience as natural gas in terms of functionality, appearance, and maintenance requirements [42] without compromising safety [60,75], however, limited data has been generated to decompose perceptions regarding potential behavioral impacts.

5. Discussion

Section 4 synthesized and distilled the empirical data on public perceptions of the hydrogen transition, and more specifically, hydrogen homes. Based on studies presented in Table 1 and supporting evidence, this section firstly ranks the critical factors of domestic hydrogen acceptance (see Table 12), before discussing research avenues and measures for overcoming barriers to domestic hydrogen acceptance based on the key findings.

5.1. Overcoming barriers to attitudinal acceptance

It is evident that attitudinal acceptance will be required if hydrogen is to compete with alternative low-carbon options such as heat pumps [121]. However, the dynamics of socio-psychological barriers concerning knowledge, awareness, and perceptions of hydrogen remain poorly understood since few studies have experimented with different types of information provision including colored information [70,86,226]. Moreover, few scholars have examined whether information provision regarding issues such as energy justice and fuel poverty may influence hydrogen acceptance [75]. At present, it remains unclear to what extent educating the public about hydrogen may yield dividends in terms of appeasing safety concerns and risk perceptions [75,86,87,121].

As a starting point, more social science research should be dedicated to assessing how neutral views based on limited knowledge and awareness may be converted into informed views of hydrogen, as a safe alternative to other residential heating and cooking technologies. Future studies should pay close attention to testing the effects of providing consumers with factual or hypothetical information, while assessing the impact of hydrogen and energy literacy on social acceptance. Overall, information provision should target understanding around priority issues such as the safety, cost, and performance of hydrogen appliances, but also extend to wider questions concerning the economic, environmental, and social impacts of hydrogen's role in the energy transition. Following Williams et al. [121], researchers should also examine whether information provision is more effective when limited to details about a single technology.

There is an underlying risk that the public may view the prospect of hydrogen appliances neutrally; unless more inroads are taken to publicize the technology, while clearly articulating its potential costs,

Table 12
This table provides a ranking for the critical factors of domestic hydrogen acceptance based on the literature in Table 1. At this stage of the transition, the foremost critical factors to social acceptance for hydrogen homes are financial costs, and knowledge and awareness.

Acceptance dimension	Critical factor	Ranking category	Description of key findings on hydrogen acceptance factors
Market	Financial costs	Critical	• Critical concerns over cost barriers (purchasing and/or running costs), and potential lack of government subsidies, financial incentives or compensation [42,68,69,75,77,86,87,89,122,123,128]
Attitudinal	Knowledge and awareness	Critical	• Very limited public knowledge and awareness of hydrogen and its production methods [42,68–70,77,86–89,121,123,130] • Very limited knowledge of hydrogen properties and its uses, or technical features of hydrogen technologies [60,68,70,77,86,88,89,121,123,130]
Community	Disruptive impacts	Major	• Major concerns over the disruptive impacts of the switchover [42,77,86,121,122,128]
Community	Distributional justice	Major	• Major concerns over distributional injustice including spatial inequities and disenfranchisement of low-income groups or those in fuel poverty [42,69,72,87]
Socio-political	Consumer disengagement	Major	• Limited consumer engagement with the energy sector beyond switching energy supplier [69,77]
Behavioral	Lived experience of cooking	Major	• Limited understanding of the lived experience of cooking [72] • Major concerns over potential disruption to the lived experience of cooking [60]
Attitudinal	Safety perceptions	Significant	• Significant concerns over safety and risk factors [60,77,86–88,128] • Significant concerns over hydrogen's invisible flame and odorless nature [42,60,68,86] • Negative perceptions or worries concerning the combustibility and flammability of hydrogen [42,60,77,86,87] • Significant concerns over hydrogen storage and carbon capture [42,68,69,88,122]
Socio-political	Environmental impacts	Significant	• Significant concerns over the impacts of hydrogen production to climate and the environment [42,68,77,86,123] • Limited support for blue hydrogen (SMR + CCS) as a long-term production strategy and/or an expressed preference for green hydrogen [68,70,88,123,128]

(continued on next page)

Table 12 (*continued*)

Acceptance dimension	Critical factor	Ranking category	Description of key findings on hydrogen acceptance factors
Socio-political	Public trust	Significant	• Skepticism regarding the tangibility of environmental benefits [42,68,69,77,86] • Limited public trust in the gas industry, government, local MPs and/or media [68, 86–88] • Skepticism about government actions and intentions [42,88]
Community	Procedural justice	Moderate	• Moderate concerns over energy vulnerabilities, fairness, and related aspects of procedural justice [42,69, 72,77] • Moderate concerns regarding realistic timeframes and/or transparency regarding the switchover and transition [42,68,69,121]
Market	Technology choice	Moderate	• Moderate concerns over potential lack of technology choice for decarbonization of heating and cooking [68, 69,77,123]
Attitudinal	Affective response	Moderate	• Neutral perceptions of hydrogen across much of society [68,87,89]
Market	Economic impacts	Moderate	• Moderate concerns over reliability of energy supply/ energy security [86,122]
Behavioral	Lived experience of heating	Minor	• Limited understanding of the lived experience of heating [72] • Minor concerns over potential disruption to the lived experience of heating and system familiarity [60, 121]

benefits, and risks. Indeed, Scovell [12] concluded that these factors could prove the most influential to HET acceptance, highlighting the need for stakeholders to maximize communication of perceived benefits over costs and risks. Furthermore, low-carbon behavioral practices appear to be positively correlated to environmental awareness [315, 316] and citizen particpation [138,313], reinforcing the need for public engagement and awareness campaigns to help establish a positive reputation for hydrogen [77].

Attitudinal factors (see Fig. 4) should be incorporated into the design of future communication campaigns targeting hydrogen acceptance [76]. Overall, there is a growing demand for factual information and clear evidence [42]. The public is interested in understanding significantly more about the financial and environmental implications of hydrogen, as well as the wider costs and benefits of the transition, with a desire for clearer information about safety issues and realistic timeframes [88]. Following Whitmarsh et al. [175], the positive public perceptions are more likely provided that "safety, efficiency, and cost criteria" are met. In turn, resources should be allocated to articulating how the utility and added value of hydrogen-fueled appliances may outweigh potential disruptions and drawbacks compared to alternative technologies [121,317,318].

Information dissemination should be targeted in a coordinated and strategic way, since "intense promotional campaigns" may not pay dividends if misdirected at consumers strongly opposed to hydrogen [115]. Key stakeholders such as government agencies, local authorities, energy companies, the gas industry, and media outlets, should communicate information to specific communities and households to increase the scope for social acceptance and counteract the risk of systemic public mistrust [24]. This could include middle-aged or retired women without higher education or technical knowledge, as well as unemployed or retired men who are skeptical about new technologies.

Finally, it has been documented that socio-structural factors such as age, gender, education, employment status, environmental values, and technical knowledge may drive or constrain hydrogen acceptance, however, the potential importance of these variables remains unclear. Future survey studies should aim to quantify the statistical significance of socio-structural factors on hydrogen knowledge, awareness, perceptions, and attitudes. In turn, attention should be paid to evaluating the extent to which knowledge and awareness may shape people's perceptions of and attitudes towards hydrogen-fueled appliances.

5.2. Overcoming barriers to socio-political acceptance

Socio-political acceptance rests on a range of factors including consumer engagement in energy markets, and public perceptions of hydrogen production pathways, environmental impacts, and the broader energy transition, as well as public trust in the emerging hydrogen landscape including its key actors and stakeholders. As a first

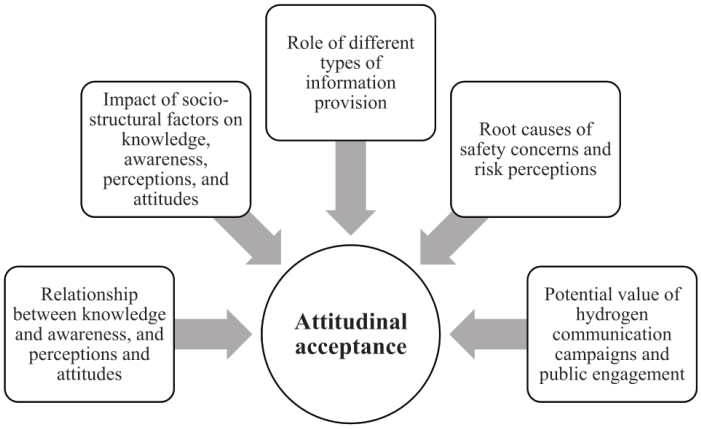

Fig. 4. This figure illustrates five key research areas for advancing attitudinal acceptance.

step this should translate into quantifying the impact of socio-structural factors on public/consumer trust in key actors and stakeholders within the hydrogen landscape. Based on the evidence presented in section 4.2, the literature should provide a deeper understanding of consumer preferences for hydrogen production pathways, which includes gauging if a transitional role for blue hydrogen is likely to be supported by the public. Additionally, studies should explicitly focus on how the public perceives hydrogen's role in reaching net zero and curbing fuel poverty.

Hydrogen acceptance studies should account for energy supply dynamics at the household level [70], as well as the potential for community-owned hydrogen projects [319]. In this respect, there is a parallel need to examine consumer attitudes towards centralized and decentralized hydrogen, electrification, and energy security. In the most recent analysis of acceptance barriers in the Australian context, it is noteworthy that reliability of energy supply ranked second behind safety [86]. Furthermore, this review has noted the potential importance of consumer disengagement in energy markets and experience with energy suppliers. A natural step forward is to test whether attitudes towards the hydrogen switchover and transition may vary according to the nature and level of consumer disengagement (see Fig. 5). Moreover, scholars should examine whether the public perceives national hydrogen strategies to be socially acceptable in respect to timeframes, costs, benefits, and risks. Researchers could also examine if consumers have any preferences regarding energy supplier when faced with the prospect of a hydrogen switchover.

5.3. Overcoming barriers to market acceptance

As described in section 4.4, market acceptance will rest on how barriers are addressed at both the macro- and micro-level. To date, there is limited evidence comparing public perceptions of cost barriers related to initial investment, running, and maintenance costs of hydrogen appliances. While some basic findings have been presented, an extensive knowledge gap remains regarding the potential interactions and trade-offs between purchase and running costs when it comes to domestic hydrogen acceptance. Notwithstanding, it is apparent that underlying financial factors will play a fundamental role in dictating decision-making at the household level and the overall trajectory of the switchover.

Studies on hydrogen futures [29] should continue to examine market acceptance at the macro-scale in relation to the wider hydrogen economy, as illustrated in the Australian context [68,86]. A starting point would be to understand public attitudes toward the timeline and trajectory of hydrogen strategy plans, accounting for sectoral priorities (industry, power, transport, and domestic), and temporal and spatial preferences. Moreover, clearer insights are needed to establish if consumers without access to hydrogen would be willing to support and pay for the switchover, and whether this may hinge on how socio-economic benefits are distributed across society. Following Scott and Powells [75], scholars should address uncertainties at micro-scale regarding society's ability and willingness to pay for the costs of the domestic hydrogen transition; examining how willingness to pay for hydrogen may vary according to housing tenure (see Fig. 6). This can help establish what kind of financial risks different segments of the population and housing stock may tolerate, and the rationale or justification behind such decisions.

Further questions should also be asked about how consumers perceive the importance of choice when it comes to heating and cooking technologies. More studies are needed to better understand whether consumers see hydrogen as promoting a smarter and more efficient heating or cooking system for low-carbon homes, compared to a like for like substitute for natural gas. This translates to the research community ensuring that heating and cooking are treated as distinct dimensions of the domestic hydrogen transition [60]. Notably, Drożdż et al. [115] found that nearly 70% of survey respondents valued increased market choice for electric car models as a spillover benefit of a scaling up in HFCVs, which could prove an interesting point for the residential context. Questions should be put to the public about how they see hydrogen fitting into the overall landscape for low-carbon technologies, and whether it is perceived as a win-win, or 'no regrets' development.

5.4. Overcoming barriers to community acceptance

The feasibility of the transition and visions for hydrogen futures [29] may rest on how the foundations of social acceptance are laid in proximity to hydrogen hubs around industrial clusters, reinforcing why research efforts should be concentrated on those communities where early hydrogen activities are planned [77]. Given the spatial dynamics of the emerging hydrogen economy in countries such as the UK, researchers should examine community acceptance in respect to industrial heritage, regional regeneration, and employment opportunities.

To date, the influence of past impacts such as industrial blight, air pollution, and unemployment in socially deprived areas, exemplified by Teesside in the North East of England [320], remains largely unattested in the context of domestic hydrogen acceptance [75]. Future studies should engage with citizens from representative parts of the country

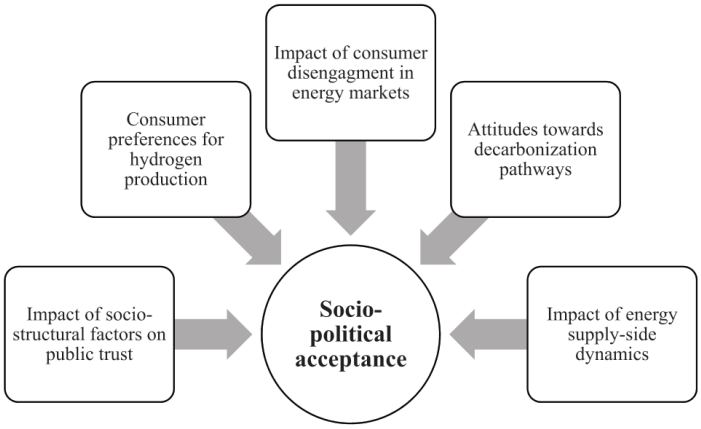

Fig. 5. This figure illustrates five key research areas for advancing socio-political acceptance.

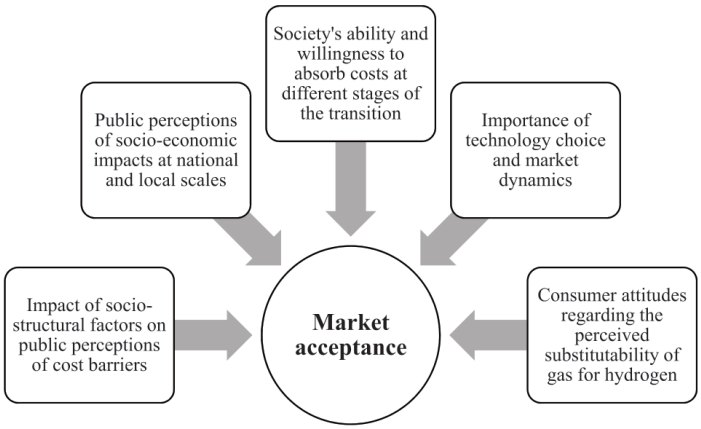

Fig. 6. This figure illustrates five key research areas for advancing market acceptance.

including communities located in urban areas in proximity to prospective hydrogen hubs and those located in off-grid rural areas, as well as population groups that fall in between these two ends of the housing spectrum. The rationale for this approach is to find out if, and to what extent, consumers excluded from the switchover may be willing to accept the hydrogen transition. Accordingly, it should become clearer how the spatial exclusivity (see Fig. 7) of the domestic hydrogen transition is shaping social acceptance [153], and whether support levels correlate to access, use, and choice.

Hydrogen's unique spatial dynamics, coupled to growing awareness about fuel poverty [321,322] make it imperative that policies and roll-out strategies strive to deliver energy justice. Sound policymaking grounded in procedural justice should pay close attention to the distribution of socio-economic costs and benefits, while factoring the welfare of vulnerable members of society into these calculations [68,87]. Otherwise, deficits in either justice dimension could potentially derail the social acceptance of domestic hydrogen, weakening the net zero agenda and contributing to further recognition injustice in the guise of fuel poverty. Given that average investment costs for heat decarbonization could prove significantly higher for households in fuel poverty, governments will need to design and implement policies to deflate socio-economic barriers. However, internalizing distributional justice into strategy plans remains compounded, since the economic costs of the hydrogen transition are difficult to forecast and quantify [87,323].

Accounting for these uncertainties, there is a need to undertake "fine-grained qualitative research" at the community and household level to better understand citizen perspectives on how changes to the energy system may impact vulnerable groups [87]. To engage with these barriers, future research should account for the immediacy of local conditions [178], as well as "the diversity and dynamics" of local communities [88]. As a starting point, research efforts should be dedicated to understanding how the hydrogen transition may impact vulnerability demographics over time, given that different deployment pathways are likely to impact the distribution and intensity of fuel poverty [72].

5.5. Overcoming barriers to behavioral acceptance

To engage with behavioral barriers, it is important to comprehend the ways in which different energy cultures may impact hydrogen acceptance at the household level. In addition to evaluating the

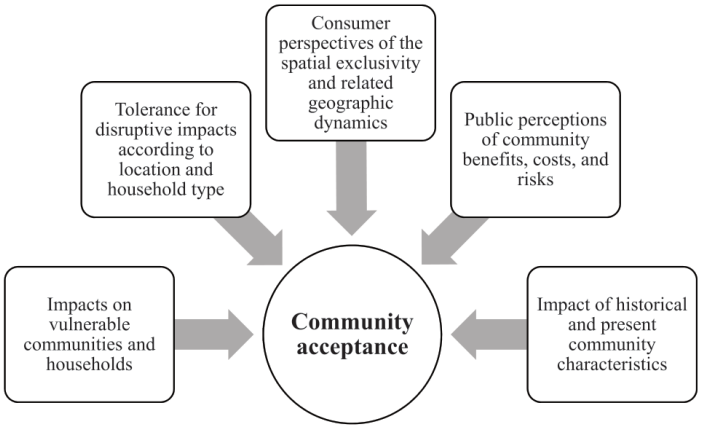

Fig. 7. This figure illustrates five key research areas for advancing community acceptance.

importance of technology choice and consumer rights, studies should flesh out how existing energy cultures could shape the hydrogen transition, paying specific attention to the interactions between cultural and behavioral dynamics. In parallel, it should be recognized that people may have limited agency since the surrounding material culture may be beyond their control. Decarbonization pathways may be decided at the national or regional level, leaving consumers with no choice about whether to remain connected to the gas grid and which fuel to use.

Future studies should also examine consumer perceptions regarding the impact of hydrogen on domestic energy practices, for example, testing to see if preferences between hydrogen appliances and other low-carbon heating technologies vary according to cultural factors including heating habits and cooking practices (see Fig. 8). Researchers should purposefully explore the potential relevance of energy cultures to domestic hydrogen acceptance. For example, comparisons between consumers familiar with low-carbon and smart technologies, versus consumers who are more disengaged with renewable and smart technologies.

Foremost, studies should address the potential impact of hydrogen homes on the energy practices of households in fuel poverty. Results already caution that misconceptions regarding the disruptive impacts of the switchover period could act as a significant barrier to acceptance. This underscores the need for transparency in information dissemination if social acceptance is to be gauged accurately, without inviting heightening risks of energy injustice. While all these points are critical to better addressing and overcoming barriers to behavioral acceptance, more tangible advances in understanding will only be possible once consumers begin to test hydrogen appliances at demonstration sites and during local trials. Already there is a desire for consumers to see the technology working, or to at least hear from others with experience of hydrogen heating and cooking systems [42].

6. Conclusions

This review paper was formulated on the premise that securing social acceptance for hydrogen technologies, especially in the domestic context, is imperative to the energy transition and the realization of a global hydrogen economy. A socio-technical systems approach was employed to better understand the human dimension of adopting hydrogen appliances for home use. Key findings have been presented in Table 12 and Figs. 4–8. This section serves to highlight the main contribution of this output to the hydrogen futures and energy transitions literature.

This review largely supports the notion that the most common barriers to renewable or low-carbon energy adoption are financial concerns, a lack of information about the technology, and socio-structural factors [324]. Evidence also suggests that social acceptance could hinge on hydrogen's potential impacts on household energy vulnerability [72], and whether consumers are granted sufficient lead time to complete the switchover [121]; in an informed and planned way [68] which minimizes disruptive impacts. In this sense, transitioning to hydrogen homes may prove comparable to the installation of domestic micro-generation technologies [134], given that both technology pathways call for social acceptance and public engagement to support large scale adoption [318]. Accordingly, households should be prepared to cover installation costs, coordinate with technicians during the changeover, and accept minor behavioral changes when switching to a hydrogen home. However, for this level of willingness to ensue, the role of information provision and public awareness campaigns must be thoroughly investigated and better understood.

This paper has demonstrated the importance of engaging with hydrogen acceptance at the attitudinal, socio-political, market, community, and behavioral level, while accounting for interactions between these five dimensions through a socio-technical systems perspective. Attitudinal acceptance, resting on how knowledge and awareness shape perceptions and attitudes, has been shown to underpin other acceptance dimensions [153]. To date, hydrogen technologies are yet to permeate the public consciousness in a meaningful way, owing to a lack of public awareness and knowledge. This review adds weight to the argument that neutral impressions of hydrogen are unlikely to be overturned, and converted into positive perceptions, absent of a strategic plan to confront acceptance barriers head on. For this strategy to be engineered, social scientists have a duty to pioneer a new wave of mixed methods research on domestic hydrogen acceptance; harnessing the power of statistical evidence from survey studies, and qualitative insights from interviews and focus groups, to increase the richness of data on public perceptions and consumer preferences.

At the socio-political dimension, there is a growing need to understand emerging views towards national hydrogen strategies, with a focus on production pathways and trust factors. *Consumer engagement in energy markets and stronger public trust in key stakeholders will help support social acceptance as the hydrogen transition unfolds.* Market acceptance rests on understanding how consumers perceive cost barriers, which translates to quantifying willingness and ability to pay for prospective hydrogen appliances and the switchover. The analysis highlights that affordability may prove *the most critical barrier to the large-scale adoption of hydrogen*

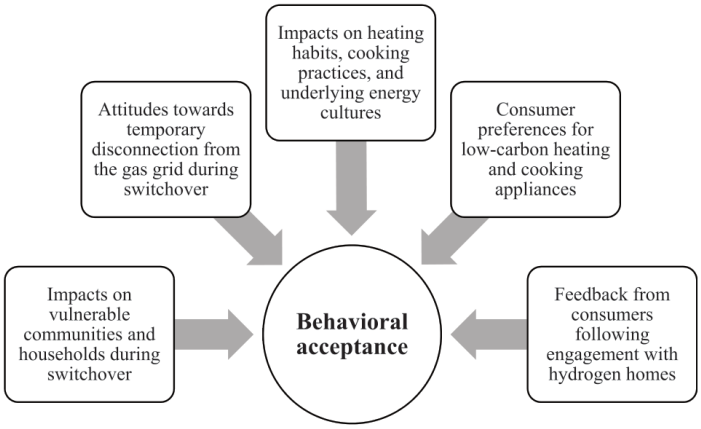

Fig. 8. This figure illustrates five key research areas for advancing behavioral acceptance.

homes.

Community acceptance calls for engagement with dimensions of energy justice, supported by a roadmap for minimizing disruptive impacts and energy vulnerabilities, which requires a comprehensive mapping of socio-structural factors such as housing tenure. Careful attention will need to be paid to communicating and minimizing the *disruptive impacts of the switchover, while alleviating concerns over distributional and procedural injustices. As a starting point, the promise of economic, environmental, and community benefits must be communicated and fulfilled to endorse the value of hydrogen homes.* Finally, studies on behavioral acceptance must shift from the hypothetical to the actual, as consumers begin to test hydrogen appliances in demonstration homes. Alongside bringing hydrogen into the public consciousness, this will enable a more legitimate understanding of the lived experience of hydrogen heating and cooking, as well as technology choice. This engagement could feasibly lead to a different ranking of critical factors. This holds equally true for other identified and potential factors, given that the five dimensions of hydrogen acceptance present a dynamic and co-evolving phenomenon [153].

To strengthen hydrogen's social standing [78], it is imperative that future studies adopt a socio-technical systems perspective; dedicated to elevating the importance of social acceptance in configuring the evolution of hydrogen technologies for the residential sector. Visions for hydrogen futures, the promise of national hydrogen economies, and the feasibility of a domestic hydrogen transition in candidate countries may rest on how this potentiality is facilitated and strengthened by key stakeholders to overcome barriers to attitudinal, socio-political, community, market, and behavioral acceptance.

Credit author statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, **Nazmiye Balta-Ozkan**: Conceptualization, Writing – review & editing, Supervision, **Ali Nabavi**: Writing – review & editing, Supervision

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX C. Beyond the triangle of renewable energy acceptance: the five dimensions of domestic hydrogen acceptance

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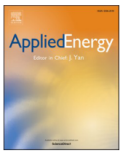

Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance

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HIGHLIGHTS

- Social acceptance research should be critical, systematic, and holistic.
- Domestic hydrogen acceptance is shaped by the interplay of five distinct dimensions.
- Hydrogen acceptance hinges on cognitive, sociopolitical, and sociocultural legitimacy.
- Hydrogen acceptance is composed of a rich matrix of potential consumer responses.
- Overcoming attitudinal and behavioral barriers is critical to the hydrogen transition.

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ABSTRACT

The 'deep' decarbonization of the residential sector is a priority for meeting national climate change targets, especially in countries such as the UK where natural gas has been the dominant fuel source for over half a century. Hydrogen blending and repurposing the national grid to supply low-carbon hydrogen gas may offer respective short- and long-term solutions to achieving emissions reduction across parts of the housing sector. Despite this imperative, the social acceptance of domestic hydrogen energy technologies remains underexplored by sustainability scholars, with limited insights regarding consumer perceptions and expectations of the transition. A knowledge deficit of this magnitude is likely to hinder effective policymaking and may result in suboptimal rollout strategies that derail the trajectory of the net zero agenda. Addressing this knowledge gap, this study develops a conceptual framework for examining the consumer-facing side of the hydrogen transition. The paper affirms that the spatiotemporal patterns of renewable energy adoption are shaped by a range of interacting scales, dimensions, and factors. The UK's emerging hydrogen landscape and its actor-network is characterized as a heterogenous system, composed of dynamic relationships and interdependencies. Future studies should engage with domestic hydrogen acceptance as a co-evolving, multi-scalar phenomenon rooted in the interplay of five distinct dimensions: attitudinal, sociopolitical, community, market, and behavioral acceptance. If arrived to, behavioral acceptance helps realize the domestication of hydrogen heating and cooking, established on grounds on cognitive, sociopolitical, and sociocultural legitimacy. The research community should internalize the complexity and richness of consumer attitudes and responses, through a more critical and reflexive approach to the study of social acceptance.

1. Introduction

In 1970, Professor John Bockris introduced the term 'hydrogen economy' [1] to describe "a system of industry, transportation, and household energy" based on piped hydrogen fuel [2]. In a 'post-Paris Agreement' world [3], there is renewed interest in realizing this vision following the launch of hydrogen strategies across parts of Europe, Asia, America, and Oceania [4]. Hydrogen is attracting attention from policymakers due to its promise of delivering synergies with other low-carbon technologies for mitigating climate change [5,6]. In response, some nations are already engaging in 'hydrogen diplomacy' [7], while energy modelers are intensifying efforts to map the "feasibility space" [8] of hydrogen systems [9,10]. Notably, low-carbon hydrogen could help contribute to the 'deep' decarbonization of residential heating. Reducing global carbon emissions from this sector is critical to the

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Nomenclature

ANT	Actor-Network Theory
ASHP	Air source heat pump
BEIS	Department for Business, Energy & Industrial Strategy
CCC	Committee on Climate Change
CCUS	Carbon capture, utilization and storage
CBM	Contingent Valuation Method
CBA	Cost-Benefit Analysis
DESs	Distributed energy systems
EJM	Energy Justice Metric
EU	European Union
FCEVs	Fuel Cell Electric Vehicles
GDNs	Gas Distribution Networks
GHG	Greenhouse Gas
GSHP	Ground-source heat pump
GW	Gigawatt
HETs	Hydrogen Energy Technologies
HHP	Hybrid heat pump
HSE	Health & Safety Executive
IEA	International Energy Agency
LADs	Local Authority Districts
LPG	Liquified petroleum gas
MLP	Multi-Level Perspective
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NIMBY	Not In My Back Yard
NGO	Non-governmental Organization
NGN	Northern Gas Networks
NZHF	Net Zero Hydrogen Fund
Ofgem	Office of Gas and Electricity Markets
PEM	Proton Exchange Membrane
R&D	Research and Development
RETs	Renewable Energy Technologies
SMR	Steam Methane Reformation
SPT	Social Practice Theory
SRP	Social Representations Theory
SST	Social Shaping of Technology
STS	Science and Technology Studies
SDGs	Sustainable Development Goals
TPB	Theory of Planned Behavior
TWh	Terawatt hour
WTP	Willingness-to-Pay

climate change effort [11,12] and already a priority for meeting European targets [13]. In response, recent forecasts from the International Energy Agency (IEA) [12,14,15] and other reports [16–18] include a potential role for hydrogen in the global buildings sector [14].[1] Moreover, alongside the European Union (EU), countries such as Japan, Australia, Germany, the Netherlands, and UK foresee a role for low-carbon hydrogen in domestic heating [15,18,20,21], with parallel interest in hydrogen appliances for cooking [22–25].

Hydrogen has become a focal point of UK energy policy [26–29], given that the country has an ageing housing stock with a poor efficiency performance by European standards [30]. Compared to countries such as Germany [31], the UK has made limited progress in retrofitting homes with poor thermal performance, due to the failure of a number of policy initiatives including the Green Deal [32]. Although the UK power sector has undergone rapid decarbonization following the phase out of coal and the scaling up of wind energy and other renewables, the residential sector has seen only minimal reductions in greenhouse gas (GHG) emissions over the last three decades [33]. In response, the Committee on Climate Change (CCC) has stated that "coordinated central decisions must be taken on the balance between electrification and hydrogen" [34].

Following the government's renewed commitment to reach 'net-zero' by 2050[2] and a more ambitious target to curb GHG emissions 78 % by 2035 [36], there has been growing policy interest in repurposing the UK's national gas grid to hydrogen [37]. Supported by a £240 million Net Zero Hydrogen Fund (NZHF), the UK Hydrogen Strategy announced a roadmap: a 'Hydrogen Neighborhood' by 2023; a village trial by 2025; scaling up to a 'Hydrogen Town' before the end of the decade [26]. The UK is seeking a front runner position through its 'twin-track' strategy, which supports both electrolytic ('green') and carbon-capture (CCUS)-enabled (blue) hydrogen production, with growing intertest in other potential production pathways [26]. In turn, investments in research and development (R&D) activities are scaling up to support this policy push towards a national hydrogen economy [38]. Moreover, the British Energy Security Strategy recently doubled the low-carbon hydrogen production target to 10GW by 2030, affirming a commitment to at least 50 % electrolytic hydrogen [28].[3]

Despite increased interest from the gas industry in (re-)introducing[4] hydrogen-fueled appliances to UK homes for heating and cooking purposes [42] and strong signals of political commitment towards this pathway [28], there is limited data on whether the public would support this decision and accept the switchover [43]. Public perceptions cannot be overlooked since it has been demonstrated that in addition to techno-economic, socio-technical, and political factors [44], socio-cultural factors may prove equally critical to achieving national energy transitions and climate change targets [45]. As technological innovation has accelerated, social and behavioral scientists have increasingly focused on understanding the factors that shape social acceptance [46–48]. In parallel, case studies of historical and emerging national energy transitions [49–51] have demonstrated the importance of social acceptance for supporting effective policies and strategies [48,52] to help accelerate the uptake of renewable energy technologies (RETs) [41]. As global renewable energy deployment has scaled up [53], such perspectives caution against viewing the energy transition narrowly as a "function of technological optimization and economic feasibility" [54]. In response, social acceptance is widely viewed as a "prerequisite for the adoption and introduction of new technologies" [55]. Notably, Australia's National Hydrogen Strategy [56] highlights the need to prioritize "socially responsible practices and policies" [57] and community acceptance [58]. It follows that understanding the "human dimension" of the hydrogen transition is critical to driving the large-scale adoption of hydrogen home appliances [59]. Arguably, social acceptance may present the greatest barrier to developing national hydrogen economies [60].

Despite some advancement towards more critical research approaches [61], the 'social acceptance matrix' [62,63] of domestic hydrogen – the configuration of potential consumer responses [61,64] to

[1] For example, under a scenario where 30% hydrogen is blended into city gas, Chapman et al. [19] estimate that hydrogen could account for 2% of global energy consumption.

[2] The Climate Change Act 2008 (2050 Target Amendment) Order 2019 [35].

[3] The UK's Gigastack project is currently the largest planned electrolyzer factory in the world [39,40].

[4] Before natural gas became commonly used in the UK after the mid-1970s, the main gas used in homes and businesses was a manufactured mixture called town gas, composed of coal and up to 50% hydrogen [41].

the proposition of 'hydrogen homes' [43,65] – remains underexplored in the literature.[5] In part, this is due to the nascency of the technology, reflected by only a handful of available studies in the academic [22,42,66–69] or grey literature [23,41,57,59,70–75]. Moreover, this deficit reflects how scholarship on the social acceptance of RETs is yet to evolve into a coherent, multi-dimensional body of research [76]. The lack of coherence and integration regarding the development of social acceptance frameworks [76] is especially pronounced for emerging energy technologies, such as distributed energy systems (DESs) [54,77] and hydrogen-fueled appliances for the home (i.e. boilers, fires, hobs, and ovens) [38]. In view of this knowledge gap, this study constructs a conceptual framework for examining the consumer side of the domestic energy transition by applying 'critical approaches' [61] to the study of domestic hydrogen acceptance. In doing so, three research questions are tackled:

- What is the current state of research on the social acceptance of the RETs?
- What are the main factors underpinning the social acceptance of domestic hydrogen in the UK?
- What are the conceptual dynamics of domestic hydrogen acceptance?

Following this introduction (Section 1), the study follows the structure illustrated in Fig. 1. Section 2 further contextualizes the study through a review of critical junctures in the field of Science and Technology Studies (STS), which have contributed towards "three waves" of social acceptance research [61]. Following Batel [61], Section 3 systemically reviews each wave of social acceptance research, spanning normative, criticism, and critical approaches, respectively. Next, Sections 4.1 and 4.2 examine the social acceptance of hydrogen energy technologies (HETs), leading to the more in-depth focus on domestic hydrogen acceptance in Section 4.3. Drawing on the findings, Section 5 presents a novel conceptual framework for exploring domestic hydrogen acceptance through five distinct dimensions. Finally, Section 6 provides recommendations from the research and concluding remarks.

2. The human factor in household energy adoption

During an influential period in the development of Science and Technology Studies (STS), the Social Shaping of Technology (SST) framework [78,79] argued that technological design and implementation [80] are shaped by "social processes, actions, and structures" [81]. Coinciding with this framework, sociologists began to explore how processes of innovation and knowledge diffusion could be understood through the lens of Actor-Network Theory (ANT) [82,83]. Notably, this approach has helped advance the study of energy transitions [84,85]. Early STS research revealed the importance of macro socio-economic forces and actor-networks in shaping technology deployment, and the role of consumers as technology adopters. In turn, scholars posited how technology is a cultural phenomenon subject to social appropriation, yet firmly rooted in political and economic ideologies [78]. Accordingly, consumers "may reject technologies, redefine their functional purpose, customize or even invest idiosyncratic symbolic meanings in them" [78].

Adding to this scholarship, domestication theory describes the process of technology adoption through four specific steps: appropriation (i.e. technologies are taken home) [86]; objectification (i.e. how a technology rearranges or constructs a physical environment) [87]; incorporation; and conversion [88,89]. As with the SST approach, consumption is seen to have an active nature, whereby households choose to incorporate a new technology into their family routines [80], until it takes on symbolic meaning and becomes normalized within a familiar setting [90]. Ultimately, if incorporation resonates at an emotional and economic level, conversion can take place through identity creation and shifts in perception of status. Indeed, in cases where new technologies have been embraced by the public, research has highlighted the importance of active end-user participation and social acceptance throughout the deployment process [91].

Focusing on the importance of the 'human factor' in household energy consumption, Lutzenhiser [92] followed in this tradition by exploring the importance of social and behavioral dimensions in terms of both 'macro-social' and 'micro-behavioral' aspects of energy use. His framework included the following factors: behavior and variability in consumption; public opinion and conservation attitudes; price and information; billing and rates; consumer knowledge and the social contexts of consumption; micro-behavioral studies of actor-building-technology systems; and macro-social organization of energy use. The author's integration of scales, and multiple behavioral, attitudinal, economic, and socio-cultural factors remains critical to better understanding the role of consumers in the renewable energy transition, as visible in the last three decades of social acceptance scholarship [61] (see Section 3). For example, two decades later, Kowsari and Zerriffi [93] proposed a 'three dimensional energy profile' framework to assess household energy use, composed of multiple exogenous (i.e. external conditions) and endogenous (i.e. household characteristics) factors. In a similar vein, Steg et al. [94] set out a future research agenda for examining "the human dimensions of a sustainable energy transition." Countering the techno-economic approach, the authors argued that alongside contextual factors, knowledge and motivations determine the feasibility of sustainable energy transitions [94].

Despite advances in the social sciences, techno-economic thinking has long dominated the academic discourse, even in the field of domestic energy studies [95]. This is striking since sociological research provides a better lens for unpacking the motivations and meanings of energy behaviors and practices [96]. Against this background, Section 3 discusses the current state of research on the social acceptance of RETs to better understanding the conceptual foundations of critical approaches towards the study of domestic hydrogen acceptance.

3. Three waves of social acceptance scholarship

As technology innovation and the pace of renewable energy diffusion has accelerated, social and behavioral scientists have increasingly focused on understanding the factors that shape social acceptance [46–48]. Social acceptance studies aim to support the clean energy transition by understanding which processes may counteract the grip of institutionally 'locked-in' fossil-based energy systems [76,97]. Key conditions for social acceptance may include support for the technology from policymakers and experts, and a lack of resistance from the NGO community, residents, local policymakers, or other representatives of public interest [98,99].

Reviewing historical developments in social acceptance theories, Batel [61] recently systematized the literature according to three waves of research (see Fig. 2). Rooted firmly in the risk perceptions literature of the 1980s and early 1990s [100–104],[6] the first wave (*Normative approaches*) focused primarily on the social side of RETs by investigating NIMBY (Not In My BackYard) syndromes and responses to the siting of renewable energy projects such as onshore wind farms [61]. Following extensive critique of the NIMBY theory throughout the early 2000s [106–109], the second wave (*Criticism approaches*) [61] was inaugurated in 2007 by Energy Policy Special Issue on the *Social Acceptance of Renewable Energy Innovation*, crystallized by Wüstenhagen et al's [110]

[5] This study uses the term social acceptance to discuss consumer attitudes and public perceptions of the domestic hydrogen transition, based on literature review findings (see Section 4).

[6] See Bickerstaff [105] for a review of psychological studies of risk perception.

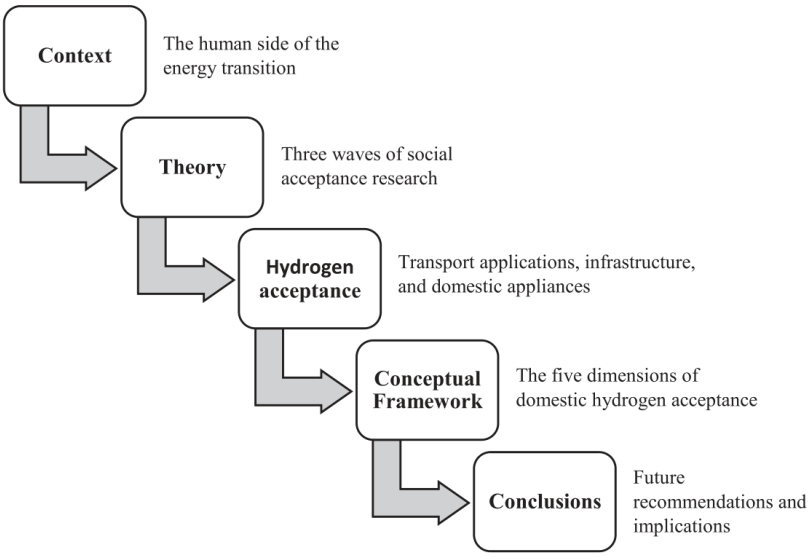

Fig. 1. Structure of the study.

Fig. 2. Overview of the three waves of research on the social acceptance of RET, adapted from [61].

conceptualization of "the triangle of social acceptance of renewable energy innovation.".

During this second wave, acceptance studies presented a stronger focus on actor-networks and scales beyond the community-level [48,99,111], incorporating deeper socio-psychological explanations [52,94,112–115]. This approach engaged more meaningfully with aspects of procedural [63,109,116,117] and distributional justice [63,116], among other factors such as perceived risk and benefit, and social trust [112,118]. Building on this literature, leading scholars have increasingly turned their attention towards better understanding people's reactions to renewable energy deployment [61]. Here, studies grapple more directly with issues of energy injustice and power relations, while communicating the "socially embedded" [61] and co-created nature of social acceptance [64] in view of socio-historical and spatio-temporal factors.

Following Batel [61], Fig. 2 provides a simple systematization of the evolution of social acceptance scholarship on the renewable energy transition over the last three decades (*italics*). This study demarcates each wave around the seminal contribution of Wüstenhagen et al. [110] (**bold**), yet retains, the original conception that these waves/periods are neither independent nor consecutive, rather they are interacting and overlapping. While criticism and critical approaches remain normative, the first wave aligned more directly to what was considered institutionally normative and mainstream thinking at the time.

3.1. Wave 1: Normative approaches – The social side of RET

Drawing on the findings of Batel [61], the first wave of social acceptance research can be loosely traced back to the mid-1990s, cemented by Gordon Walker's review paper [119] on public attitudes towards four types of RETs (hydroelectric power, geothermal, tidal, and wind). Responding to a deficit in understanding "the perceptual and social dimensions" of renewable energy deployment, Walker called for more research dedicated to providing "…a clearer, harder and more sensitive and sophisticated awareness of public attitudes…and a greater understanding of how attitudes are formed, changed and developed," with experience and over time [119]. Additionally, the article highlighted the extent to which studies on the public acceptance of RETs remained dwarfed by research on nuclear power [119], concentrated foremost on risk perceptions of radioactive waste [101,102,120–122] and the NIMBY phenomenon [123,124], to which Wave 1 owes its foundations [61].

3.1.1. Not in My back Yard syndromes and responses

NIMBY 'syndromes' [125] and 'responses' [126] – whether rooted in the selfish pursuit of maximizing personal-utility [127] or rational acts of 'place-protection' [108] – have often been cited as one of the prevailing reasons for public opposition to energy projects and technologies [107]. 'NIMBYism' takes effect when citizens object to energy projects being sited in proximity to their property or local area [108,128], which typically supersedes general support they may otherwise hold for the

project [107]. NIMBY objections may be strongly linked to visual intrusion, especially in the case of wind farms [129], while noise and effects on biodiversity are other motivational factors [106].

NIMBY attitudes have been linked with opposition to windfarm planning applications in England and Wales during the early 2000s [130]. Based on a more recent dataset (2012–2018), Roddis et al. [131] found that rural communities located close to onshore wind and fracking installations were more opposed to these technologies than people living in urban areas. A wide range of case studies present similar findings on the prevalence of NIMBY [128,132,133]. For example, Mueller et al. [134] observed that proximity to high-voltage transmission lines in Lower Saxony, Germany, led to increased risk perceptions and decreased citizen support for grid expansion. In the case of hydrogen refueling stations, Iribarren et al. [133] found that Spaniards were supportive of the infrastructure, but objected to these facilities being located within residential zones. Notwithstanding, contradictory evidence suggests that spatial determinism may be a weak explanation for the NIMBY phenomenon [108]. Alternatively, researchers have shown that some energy projects including wind farms may give rise to an 'inverse NIMBY syndrome' [135], which sees local support positively correlated with spatial proximity to the project site [106].

Marking a departure away from early thinking on the social side of RETs [61], the notion of NIMBY became a highly contested factor of social acceptance [107]. In turn, most schools of thought moved from questioning to debunking its validity as a concept [106]. Writing in 2006, Wolsink [136] memorably argued that "the application of the NIMBY argument as a tool for analysis is scientifically perilous, and it should be abandoned." His critique concluded that NIMBY "obscures the real motives and impedes our understanding of what is really happening in facility siting conflicts" [136], announcing the imminent shift towards a new wave of social acceptance research.

3.2. Wave 2: Criticism approaches – The social acceptance of RET

The second wave marked a departure away from engaging with questions of social acceptance through the lens of NIMBY. Instead, scholars such as Devine-Wright [107] and Walker et al. [137] turned their attention to examining actor-networks and scales that extend beyond the local level, while also investigating socio-psychological and contextual aspects linked to perceived benefits, costs, and risks. Section 3.2.1 outlines the first focus area with a brief discussion of 'post-NIMBY' theories [107], while Section 3.2.2 details the other prominent 'strand' of the criticism approach [61] through an overview of socio-psychological and contextual factors.

3.2.1. Post-NIMBY theorizing: Place attachment and place identity

The discussion of social acceptance in relation to spatial factors and the associated critique of NIMBY has been enriched by nuanced analysis of the role of 'place attachment,' which corresponds broadly to "one's emotional bonds with the local area" [52]. Emotional bonds may develop in the form of 'place inherited' and 'place discovered' attachment, or otherwise be absent in the case of "non-attachment" [138,139] (see Table 1). Place attachment is positively correlated to the duration of this relationship [108] and gives rises to 'place identity' [140], which Proshansky et al. [141] define as "a cluster of positively and negatively valenced cognitions of physical settings." Accordingly, place attachment should be considered as both a socio-psychological and geographical factor of social acceptance [111].

Moving beyond NIMBYism by uniting these streams of thought, Devine-Wright [108] attributed local resistance to the disturbance of "pre-existing emotional bonds," which threatens place identity and motivates 'place-protective' actions [140]. Exploring the interactions between place attachment and place identity in relation to the construction of high voltage power lines, Devine-Wright [140] found that individuals with ties to their surroundings in the form of 'place discovered' attachment were less likely to express technology acceptance, most likely stemming from finer attunement to the potential negative impacts of energy-related infrastructures on their community. Additionally, the study reported that project-related variables such as perceived impacts, procedural justice, and trust were more significant in explaining public opposition than place attachment or socio-demographic variables.

Table 1
Theories of place attachment.

Source	Type of place attachment	Core foundations	Operational significance
[298]	Place inherited/ traditional	Rooted in dailyness and familiarity	• Surroundings taken for granted • Deep connections sustained to place of residence
[298]	Place discovered/ active	Rooted in the conscious decision to live in a specific location	• Active interest in surroundings • Strong sense of ideological identification
[138]	• Place alienation • Place relativity • Placelessness	Rooted in non-attachment to place of residence	• Dislike and estrangement to place of residence • Ambivalence and conditional acceptance • Indifference to surroundings and no desire for developing emotional bonds to place of residence

Source: Authors' compilation.

Geographical factors such as "place, landscape, distance, decay, and territory" may have a significant impact on social acceptance, especially at the community level [142]. More specifically, it has been argued that spatial proximity and scale are potential determinants of community support, which result in "heterogenous patterns" of acceptance [54]. Supported by an associated study on the local acceptance of wind power projects [109], Wüstenhagen et al. [110] suggested that community acceptance follows a U-shaped curve, which sees acceptance go from high to relatively low during the siting or construction phase, before reaching a higher level of acceptance once the project becomes operational.

While such studies and related post-NIMBY theories typically look at a specific energy project or technology, it has also been argued that place attachments and identities may prove influential to how society responds to the climate change crisis [143]. Place attachment need not be limited to one place and to the local scale but can extend to the 'poly-local' and 'polyscalar', which may motivate public engagement in climate change action vis-à-vis the adage, "think globally, act locally" [144]. The shift towards 'polycentric'[7] modes of thinking about social acceptance [76,145] and the governance of energy infrastructure [146] coincides more concretely with the ongoing wave of scholarship (see Section 3.3). Notwithstanding, in both political and public discourse, there is still a prevailing tendency towards bracketing issues of community acceptance under NIMBYism.

3.2.2. Socio-psychological and contextual factors

As conceptualized by Stephenson et al. [147] in their 'Energy Cultures' framework, there is a relationship between "cognitive norms" (i.e. beliefs and values), "energy practices" (i.e. activities and processes), and the surrounding material culture associated with a technology and where it is used. More systematically, the Theory of Planned Behavior

[7] Referring to "the many different centers of decision-making at different scales" [145].

(TPB) posits that behavioral intentions are determined by "attitudes toward the behavior, subjective norms, and perceived behavioral control," which together with consumer perceptions "account for considerable variance in actual behavior" and decision-making [148]. Moreover, environmental psychologists have documented how a discrepancy often exists between stated values, beliefs and intentions, and observable behavior, resulting in a 'value-action gap' [149,150], otherwise often discussed in terms of an 'intention-behavior gap' [151] or 'knowledge-action gap' [152].

In addition to reconceptualizing the notion of NIMBY and highlighting the importance of 'space and place' to the study of low-carbon energy transitions [108,142,153], the second research wave developed a more explicit focus on how social acceptance is configured by interactions between socio-psychological [115] and contextual factors [52] (see Table 2). Socio-psychological factors depend on individual subjectivity and personal values, which may also explain public attitudes towards climate change [154] and the sustainable energy transition [155]. While classifications of these factors vary somewhat within the literature, socio-psychological factors are regarded to shape public perceptions of contextual factors [52]. Furthermore, Wolsink [76] posits that contextual factors reveal the impact of external conditions which may drive, trigger or block technology acceptance.

During the period of post-NIMBY theorizing, socio-psychological and contextual factors were mainly analyzed through the lens of perceived benefits, costs, and risks [112,114,156,157]. At the individual level, "perceived benefit" relates to the probability that a given action or behavior will yield positive results [157], whereas "perceived risk" refers to perceptions regarding the uncertainty and potential negative effects of a specific action or behavior. As argued by Wüstenhagen et al. [110] and Steg et al. [94], social and community trust influence how the public perceives the costs and benefits of low-carbon energy transitions.

Focusing on 'controversial' electricity generation sources, Bronfman et al. [118] constructed a "causal-trust acceptability model" in which acceptability is determined by social trust in regulatory authorities, in addition to perceived risks and benefits. Investigating the relationship between benefit and risk judgements for hydrogen transport (cars and buses) in the Netherlands, Montijn-Dorgelo and Midden [158] found that consumers are more likely to perceive stronger benefits and lower risks when they trust the actors involved in hydrogen projects. Interestingly. Gupta et al. [113] found that *perceived risk* was the most frequently investigated determinant of public acceptance, followed by *trust*, *perceived benefit*, and *knowledge*.[8]

Table 2
Socio-psychological and contextual factors underpinning renewable energy acceptance.

Socio-psychological Factors	Contextual Factors
• Place attachment	• Fair procedures
• Place identity	• Environmental impact
• Trust	• Energy price
• Values	• Quality of supply
• [52]	• Location
	• Objective dimensions of energy goods [52]
• Beliefs and attitudes	• Performance
• Motives and intentions	• Cost
• Perceived behavioral control	• Fashion
• Cost-benefit appraisals	• Familiarity
• Personal and social norms [299]	[176]

Source: Authors' compilation.

[8] *Individual differences*, *attitudes*, negative affect, technology characteristics and *the* role of societal actors were other relevant determinants, albeit less frequently reported.

Illustrating the importance of these factors in the context of energy-producing systems, Sjöberg [159] showed that perceived risks were regarded as more important than perceived benefits, except in the case of wind power. However, in the absence of perceived benefits, consumers are less likely to tolerate even minor levels of risk [160]. Furthermore, it remains critical that benefits flow to the public and the environment [52], as opposed to industry or specific stakeholders, unless these stakeholders can better represent marginalized social groups such as those in fuel poverty [160]. While risk perceptions strongly influence public support for the building of large-scale infrastructure projects such as a nuclear power plant, perceived benefits may prove to be the "key predictive factor" when considering the social acceptance of new sources of electricity generation [118] or low-carbon heating technologies [98].

Under the worst-case scenario, Cohen et al. [161] state that, social acceptance should correspond to a "welfare neutral" outcome for each agent involved, whereby the negative and positive aspects of new energy infrastructure projects are balanced out. Although welfare neutrality may not necessarily secure higher welfare for society, this economic framing is suggested to counteract definitions of social acceptance that impart excessive agency on members of respective social units [48]. At the collective level, cost-benefit evaluations and risk perceptions reflect societal implications such as public safety and environment health, whereas individual implications involve personal resources such as time, money, and comfort [52]. While technical experts employ detailed risk assessments to arrive to their conclusions, the decisions of the public regarding perceived costs, benefits, and risks are influenced by non-technical sources of information such as media representations, and ordinarily based on prior experiences and emotional factors [100,162,163].

3.2.3. *The triangle of social acceptance of renewable energy innovation*

During the early 2000s, scholars such as Devine-Wright [107] had underscored the multi-dimensionality of social acceptance, for example, by examining physical, contextual, political, and institutional, socio-economic, social and communicative, symbolic and ideological, local and personal dimensions in relation to wind farms. In 2007, Wüstenhagen et al. [110] consolidated the criticism approach by expanding on the importance of the institutional and social environment [76]. The authors proposed a tripartite framework for understanding the social acceptance of renewable energy innovation, composed of socio-political, community, and market dimensions [110]. The framework added a distinctive 'multi-level' element to the study of social acceptance, characterized by dynamic interactions and co-evolving processes [76], somewhat comparable to the Multi-Level Perspective (MLP) framework [164]. The MLP explains technological transitions according to the interplay of processes across three distinct levels: the socio-technical landscape (macro-level); the socio-technical regime (*meso*-level); and the niche (micro-level) [165,166].

Socio-political acceptance is the broadest of the three dimensions, operating at the macro or national level [48]. This dimension encompasses how the public and other stakeholders view the policy environment surrounding the deployment of new energy technologies, which is typically gauged through opinion polls [110]. The implementation of effective policies by regulators and policymakers is recognized as a key mechanism for fostering market and community acceptance [167]. Market acceptance "operates at a *meso*-level between national politics and local communities" [167], involving industry actors such as incumbents, small and medium-sized enterprises (SMEs), and intermediaries [168]. At this level, investors typically act as energy suppliers and consumers as technology adopters [167], although households may be regarded as both investors and consumers when they purchase energy appliances [110]. The investment landscape shapes the potential for social acceptance by directing how companies and consumers contribute towards technology adoption [55].

In contrast to market acceptance, which is linked to how transition

Table 3
Actors and factors behind social acceptance of renewable energy technologies.

Acceptance dimension and definition	Scale	Actors	Factors
Sociopolitical acceptance The ability for regulators, policymakers, and other key stakeholders to craft effective policies or frameworks that effectively foster and enhance community, market, and public acceptance of RETs [110,167]	**Macro** Supply-side acceptance of RETs at the policy or national level [48]	• Regulators	• Technology type, scale, and context
		• Legislative authorities • Policy actors • Key stakeholders • General public [76,167]	• Legal and regulatory frameworks • Institutional capacity • Political commitment [111,167]
Community acceptance The extent to which new renewable energy projects or appliances are invested in or trusted by local stakeholders, and the scope of justice (procedural and distributional), trust and legitimacy [110,167]	***Meso*** Acceptance of new renewable energy infrastructure, facilities, and technologies at the local level [48]	• Local stakeholders	• Infrastructure and resource availability
		• Local authorities • Residents • End-users [76,110,167]	• Historical and cultural heritage • Place attachment • Participatory project siting • Transparent communication and planning procedures • Local stakeholder engagement • Recognition of externalities [110–111,142,167]
Market acceptance The extent to which investors want to support the manufacturing and use of RETs, and the level of market uptake [110,167]	***Meso*** Acceptance of a renewable energy technology or application at the household and organization level [48], which operates at a *meso*-level between national politics and local communities [167]	• Incumbents	• Competitive installation and production costs
		• Small and medium-sized enterprises (SMEs) • Producers • Consumers • Distributors Investors • Other intermediaries [76,167,168]	• Cost-competitiveness of the technology for consumers • Financing mechanisms for producers and consumers • Business models and tariffs • Mechanisms for information and feedback [167,168]

Source: Authors' compilation.

and transaction costs compete against alternative technologies [167] and gauged in terms of adoption, community acceptance is contingent upon the willingness of local stakeholders to invest in new energy projects or appliances and measured according to participation in planning processes [110]. This willingness depends partly on how local citizens perceive levels of disruption or inconvenience [169]. Moreover, community acceptance rests on whether costs are perceived to be distributed equitably, alongside fair decision-making processes, characterized in terms of procedural and distributional justice (see Section 3.3.2), and trust at the community level [110]. When planning processes are non-participatory and lack transparency, and costs and benefits are distributed disproportionately, social acceptance is more likely to waver [132,170,171]. Finally, trust depends on how the local community perceives the intentions of investors and external actors, and whether they consider information to be reliable [172]. To promote fairness and equity for all stakeholders, it follows that the low-carbon transition should actively engage with issues of energy justice and trust [171], which has become a pillar of the third wave of research (see Section 3.3).

When distributional costs are accounted for, residents are more likely to have positive views of perceived energy justice, as exemplified in the context of landmark renewable energy projects in Denmark and Germany [173]. Such projects highlight the importance of bottom-up consultation processes and information dissemination as key mechanisms for securing energy justice and social acceptance [173]. Public perceptions of transparent and participatory energy-system implementation processes increase social acceptance [174]. Conversely, social acceptance appears to decrease when the public has pronounced reservations about the profit motives of energy companies [41,175] and the legitimacy of government pledges [41,59,74]. Ultimately, social acceptance is more likely when institutional frameworks and business models foster stakeholder participation and transparent communication procedures [176], with citizens assured that technology adoption will provide local economic, environmental or social benefits [77,98] without disenfranchising vulnerable members of society [160].

Representing the contribution of the criticism approach, Table 3 provides a high-level overview of the scales, actors, and factors of each social acceptance dimension based on the original conceptualization [110], and subsequent modifications and additions to the framework, and applications to different renewable energy contexts.

3.2.4. *The transition from criticism to critical approaches*

Following the seminal contribution of Wüstenhagen et al. [110] and growing interest in themes of energy justice [171], several studies [62,145,174,177,178] have demonstrated the importance of multiple social acceptance factors (see Table 4), while enriching theoretical perspectives. Notably, in 2008, Devine-wright [111] called for more "interdisciplinary research…with a greater emphasis upon the symbolic, affective and socially-constructed nature of beliefs about renewable energy technologies." Having examined the investment and community acceptance side of wind and solar systems during the early decades of

Table 4
Applications of social acceptance approaches, 2008–2018.

Study	Social acceptance dimensions and factors	Details of study and key findings
[111]	**Personal** Age Gender Class Income **Social-psychological** Knowledge and direct experience Perceived fairness and levels of trust Political beliefs Environmental beliefs Place attachment **Contextual** Technology type and scale Institutional structure Spatial context	• Builds on theories developed from the field of environmental psychology [54] • Places a more direct focus on the consumer in terms of socio-demographic and socio-psychological factors • The contextual and spatial focus extend the analysis to the macro-level, with the contextual category echoing the socio-political dimension described by Wüstenhagen et al. [110] • Highlights how support for RETs may vary across geographical scales
[167]	**Socio-political** Strong institutional capacity Political commitment Favorable legal and regulatory frameworks **Community acceptance** Prolific community and/or individual ownership and use Participatory project siting Recognition of externalities Positive public image. **Market acceptance** Competitive installation and/or production costs Mechanisms for information and feedback Access to financing	• The framework separates the political from societal/community aspects [168] • Explains faster diffusion and stronger domestic markets for wind energy in Denmark compared to India, and for solar power in Germany compared to USA during the 1990s and 2000s • Denmark satisfied every criterion except for that of transparent regulatory changes, and Germany satisfied every criterion except for competitive installation/production costs • India and USA satisfied only three of the criteria
[62]	**Project specific and technical** **Ecological** **Social, societal, and emotional** **Procedural and formal** **Political** **Macro-economic/national/spatial**	• Locals frequently have rational arguments for their resistance to high voltage lines and wind farms • Mistrust among stakeholders significantly hampers the progress of negotiations and participatory processes • Standards for participatory processes and quality standards should be implements by project planners • Consumer attitudes are often intractable, therefore, comprehensive information about project proposals should be disseminated to the public as early as possible
[168]	**Governance and regulation** (i.e. socio-political) **Socio-cultural and public acceptance** (i.e. community) **Markets and innovation** (i.e. market)	• Unpacks the interrelations between these dimensions across different geographical scales (international, national, and local) • Argues that the belief systems or social representations of key actors operating at different scales are critical to the process of social acceptance • Analyzes the role of 'middle actors' in driving technology diffusion and acceptance • Middle actors play an important role in mediating processes of change between scales
[179]	**Material arguments** Aesthetic factors Environmental factors Economic factors Project details	• Material arguments (i.e. impact on wildness, project size and visual impacts) were more significant factors of community acceptance for onshore wind and solar farms than attitudinal/social influences • Visibility (aesthetic), installed capacity (project details), social deprivation (demographic) and year of planning application (temporal) were statistically significant factors for both technologies • Solar farms are more likely to be sited in deprived areas • Onshore wind farms are more likely to be sited in wealthier areas
	Attitudinal/social influences Demographic factors Political factors Temporal factors Geographical factors	

Source: Authors' compilation.

market deployment, Sovacool and Ratan [167] argued that each acceptance dimension should be met "holistically in order for investors and users to embrace renewable energy." Applying an energy justice lens, Roddis et al. [179] investigated the impacts of community acceptance on planning applications for onshore wind and solar farms in Great Britain between 1990 and 2017. Such studies reflect a recent observation by Busse and Siebert [180] in the context of renewable energy projects with land use impacts, namely, that "trust, participation, knowledge, prior experiences, and economic, and visual aspects" are frequently cited as the influencing factors of social acceptance.

Above all, the conceptualization of social acceptance proposed by Wüstenhagen et al. [110] and subsequent modifications to this framework [48,167,168], reinforce the extent to which social acceptance may hang in the balance due to deficits within a specific factor; or be undermined by a combination of deficiencies across multiple factors and dimensions. Furthermore, the same factors may play out differently and carry different weight according to the energy technology in question.

3.2.5. Ten years on from the triangle of social acceptance of renewable energy innovation

Despite progress in some respects, ten years on from the three-dimensional framework [110], Devine-wright et al. [168] observed that few studies had succeeded in addressing the multi-dimensionality of social acceptance. On the one hand, this is striking since over 400 studies had cited Wüstenhagen et al. [110] by the end of 2016. However, equally noteworthy is that over 800 additional studies have cited the seminal work since 2017, according to the Web of Science database (see Fig. 3). While encouraging in terms of numbers, to the authors' knowledge, no attempt has been made to identify how many of these studies fall within the scope of critical approaches. Notwithstanding, it is evident that criticism approaches remain the most prolific wave of research on social acceptance to date.

Writing in 2017, prior to an overall surge in social acceptance studies, Devine-wright et al. [168] advanced the research domain by examining the importance of "social representations held by key actors…where a polycentric perspective places particular emphasis on ways that middle actors mediate processes of change between scales" [168]. Expounding on this shift towards polycentric thinking and associated critical approaches to the study of social acceptance, Section 3.3 systematically describes the ongoing research wave, following the contributions of Batel [61], Batel and Devine-Wright [64], and one of protagonists of the second wave, Maarten Wolsink [76,181].

3.3. Wave 3: Critical approaches – People's responses to RET

As described in Fig. 2 and internalized throughout this historical analysis vis-à-vis Batel [61], each research wave is neither strictly independent nor consecutive, but rather interconnected and overlapping.

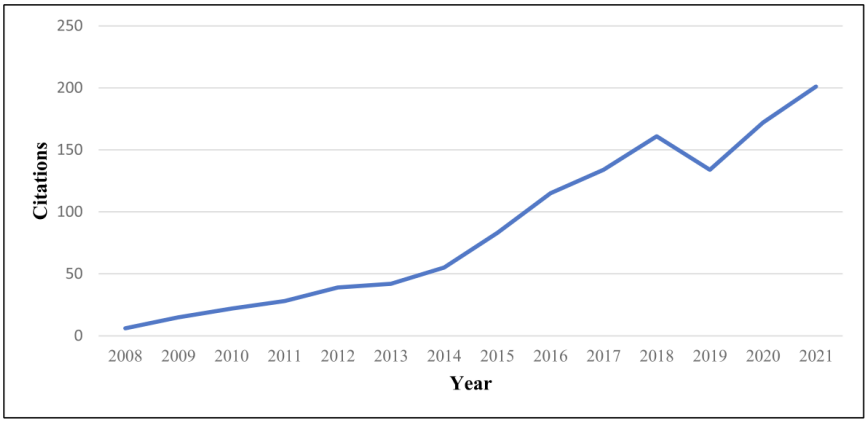

Fig. 3. Citations per year for the "Social acceptance of renewable energy innovation: An introduction to the concept [110,296], as of Web of Science database [296].

Notwithstanding, it is instructive to link the start of each wave to a key contribution to the literature, such as Walker [119] for Wave 1 in 1995 and Wüstenhagen et al. for Wave 2 in 2007 [110]. Coinciding with recent critical junctures in political and environmental history,[9] Wave 3 can be traced back to 2015 when Batel and Devine-Wright [64] set out to establish "a better understanding of people's responses" to RETs by drawing on insights from Social Representations Theory (SRT). Thereafter, Batel and colleagues [185] linked together theories of behavior, practice, and social representations by merging Social Practice Theory (SPT) [186,187] with SRT in a single framework. The framework proposed a more comprehensive way to understand different junctures of the "social change process" towards a sustainable energy transition and low-carbon society. In parallel, Miller et al. [188] proposed the "socio-energy systems" policy framework, predicated on the notion that energy transformations co-evolve within and shape the fabric of society, culture, and politics, wherein "people and organizations are complex entities – with histories, identities, and cultures – that require careful and sophisticated analysis."

Whereas some technologies such as nuclear power have traditionally been associated with political elitism [189] and technocratic ideologies [190], renewable-based energy systems may present opportunities to create a more democratic, decentralized and community-based energy future [191]. This prospect has seen 'clean energy' politics increasingly associated with the notion of 'energy democracy' [192–194], demonstrating the far-reaching implications of energy choices on the socio-political landscape [195]. Contrary to this line of thinking, critical approaches depart from previous scholarship by unpacking how RET deployment and the decision processes behind it are "often apolitical, unjust and undemocratic, or just another materialization of the neoliberal capitalist system" [61]. While the third wave is multifaceted with several emerging themes [61], it has materialized around at least four key areas which are further taken up in this analysis (see Table 5).

This focus brings new insights to the socio-spatial, socio-cultural, contextual, and attitudinal (i.e. socio-psychological) dimensions of social acceptance, while retaining a multi-dimensional approach towards rigorous inquiry. For example, in the context of DESs, Von Wirth et al. [54] underlined how social acceptance studies should examine spatio-temporal factors "to detect socio-spatial patterns," alongside "an in-depth actor analysis and temporal analysis of the diffusion process."

[9] Foremost, the passing of the United Nations 2030 Sustainable Development Goals (SDGs) [182–184] and the Paris Climate Agreement [3].

Table 5
Four pillars of critical approaches to the study of social acceptance.

Scope of pillar	Perspective and framing	Key studies
Exploring the spatial dynamics of social acceptance through relational frameworks	Social acceptance is viewed as a multi- and cross-scalar phenomenon, operating within the energy production-consumption nexus	[76,153,202,300]
Examining the impacts of pursuing 'just' energy pathways	Social acceptance contends against a pandemic of energy poverty rooted in the prevailing socio-political landscape	[171,173,179,198,301,302]
Exploring the influence of temporal and socio-historical factors on the energy transition and community acceptance	Social acceptance is linked to time, place, and space, such as the legacy of industrial heritage and absence/presence of regional energy cultures	[131,222,223,225,226,303,304]
Overcoming the reductionist nature of previous research waves (i.e. normative and criticism approaches)	Social acceptance is characterized by a matrix of potential attitudes and responses, reflecting the complexity and often paradoxical nature of human emotion	[54,76,243,305]

Source: Authors' compilation.

The next Sections (3.3.1–3.3.4) tackle each of the four areas in turn.

3.3.1. The spatial dynamics of social acceptance: macro-, meso- and micro-scales

Social acceptance is governed by complex and multi-layered interactions between multiple stakeholder groups [168] and involves "mutually influencing processes" that cut across national, communal, and local scales [76]. These processes – whether scientific, technical, institutional, socio-economic, cultural, or organizational – are context-

specific and polycentric in nature [76], with several governing authorities operating at different scales [196,197]. As low-carbon transitions play out within dynamic 'territorialities' [153] and across different geographies, changes are thus "modulated by uneven spaces and scale" [198].

There are three specific geographical scales or levels at which these processes interact: the macro-, *meso*-, and micro-scale [48,168]. The macro-scale represents "the general, policy or country level" [48], characterized by large-scale infrastructure projects that directly impact national energy supply, such as the building of nuclear power plants or offshore wind farms. The *meso*-scale refers to how energy projects develop through mechanisms at the local, community or town level, while the micro-scale is relevant to technology implementation at the building, household, or organization level [48,111]. Further unpacking the characteristics of the micro-scale, Després [199] described the household as a "material located" and "political-economic" entity, where "continuity and permanence" reside; reproduced by the activities, relationships, ideas, and values of its occupants. As the modern, domestic environment becomes increasingly populated by smart home technologies and devices [200], this social reproduction of continuity and permanence may be reconfigured along new contours. Optimally, this reconfiguration should reflect changing values and priorities aligned to environmental citizenship and energy conservation [150,201].

Illuminating the differences between these scales and their respective links to economic, political, and social dimensions of technology acceptance in the context of wind energy projects, Fournis and Fortin [202] proposed the following analytical levels: macro-economic, *meso*-political, and micro-social. At the micro or micro-social scale, acceptance is determined directly by the decisions of end-users [203], as they choose to support and adopt, or resist and reject energy technologies for different motivations [115]. After all, even the best technology serves little purpose unless people genuinely use it [115,204] and preferably as intended by its designers [205].

Broadly speaking, energy transitions involve simultaneous shifts across all three scales: at the macro-scale through changes in electricity and gas networks; at the *meso*-scale as interactions between consumers and suppliers are altered; and at the micro-scale as households change their technology preferences. Accordingly, energy researchers should adopt a sensitive multi-scalar perspective [206] to reveal information about individual perceptions and attitudes toward clean energy technologies [207,208] and their land-use impacts, which should be examined "case-to-case with data-driven impact evaluation" [209], incorporating a direct focus on social aspects and environmental justice implications [210].

Table 6
Definitions and implications of energy and fuel poverty.

Energy Poverty	Fuel Poverty
• Lack of access to energy infrastructure, especially electricity and modern cooking fuels, and affordability challenges for securing energy goods and services [306]	• Households cannot afford adequate domestic energy services given their current income level [308]
• Gives rise to reliance on traditional use of biomass for heating and cooking [211,271,307]	• Forced to spend more than 10 % of household income on basic energy costs [212]
• Households may be forced to forego essential services or capabilities, or choose between eating or heating [211,271,307]	• Households have higher than average fuel costs but lower than average income [309]

Source: Authors' compilation.

3.3.2. Just transition pathways: Fuel poverty, energy justice, and social acceptance

Households facing energy poverty and/or fuel poverty are often victims of pervasive energy injustice and inequality. While these terms should be differentiated according to context, they share similarities in terms of distributional injustice (see Table 6). Bartiaux et al. [211] describe the source of energy poverty as "a lack of material resources and economic power," which can corrode a wide range of physical, sensory, psychological, intellectual, emotional, and spiritual capabilities. Energy poverty remains a systemic issue in the UK, since England's flagship fuel poverty program – the Warm Front Home Energy Efficiency Scheme which ran between 2003 and 2013 – while successful in reducing the level of fuel poverty for 2.36 million homes, failed to lower the national rate of fuel poverty [212]. In response, Demski et al. argue that a more salient approach considers energy as "a need and basic right" [207], thereby seeking explicit provision and protection for vulnerable parts of society. Sovacool and Brisbois [213] have likewise drawn attention to the importance of protecting human rights throughout the production and consumption of energy.

Against this backdrop, energy justice has developed into a prominent interdisciplinary research area [171,214], strengthened since 2015 by the passing of the United Nations 2030 Sustainable Development Goals

Table 7
The Energy Justice Framework.

Energy justice tenet	Premise and focus	Operation and application
Procedural	Focuses on the decision-making and informational aspects of energy developments to achieve social goals [171,215,216,310]	Examines how stakeholders participate in the planning of rules and laws, exploring the configuration of stakeholders involved in influencing decision-making processes [171,215,216,310]
Distributional	Depends on how the social goods and ills of a new technology are distributed across the population [170–171,311]	Calls for more robust quantitative and qualitative exploration of the co-benefits and externalities of renewable energy deployment [171][1]
Recognition	'Post-distributional' in the sense that inequalities should be contextualized and understood according to their societal impacts [312]	Aligned to fair representation, freedom, and safety for all individuals [313]
Cosmopolitan	Applies procedural and distributional justice to the global scale, based on the premise that every individual has intrinsic worth that should be safeguarded [216]	Promotes a collaborative approach towards recalibrating energy cultures in a direction aligned to positive global change [217]
Restorative	Focuses on repairing the damage inflicted on society or nature [218]	Offers a built-in mechanism for safeguarding the welfare of local communities and nature by obligating decision-makers to factor in the long-term social and environmental costs of energy-related activities [218]

Source: Authors' compilation.
[1] Cautions against overreliance on CBA as a tool for judging the equitability of energy projects [171].

(SDGs), especially SDG7 targeting "Affordable and Clean Energy"[10] [182–184]. McCauley et al. [171] describe energy justice as "a conceptual, analytical and decision-making framework" designed for understanding the temporal and spatial dynamics of ethical issues related to energy activities. The framework strives to secure a sustainable energy system rooted in fairness and equity [179] by identifying which stakeholders should be involved in resolving such issues [171]. Formally, the framework includes three core tenets – procedural, distributional, and recognition justice [215] – which are increasingly discussed alongside two additional dimensions, namely, cosmopolitan [216,217], and restorative justice [218] (see Table 7). Notably, Applied Energy Special Issue on "Low Carbon Energy Systems and Energy Justice" highlighted the importance of merging energy justice with other theoretical frameworks such as social acceptance to drive a more nuanced understanding of a 'just' energy transition [171].

The links between fuel poverty, energy justice, and social acceptance have recently been explored across a range of national contexts and scales, with social science researchers applying multiple theoretical approaches [171,179]. For example, Heffron et al. [219] proposed the Energy Justice Metric (EJM) to provide a more representative measure of energy justice than offered via on cost-benefit analysis (CBA). The EJM accounts for the full energy lifecycle of a technology, adopting an "inequality-correcting" approach that enables decision-makers to proceed more responsibly when assessing technology pathways. The modeling tool operates by quantifying the energy justice performance of different countries based on data from national governments and international institutions. Sareen and Haarstad [198] examined the socio-technical and energy justice aspects of sustainable transitions in terms of "the co-evolution of institutional, material and relational change," accounting for the 'cross-cutting' implications of 'multiple spatialities' and normative effects. Such approaches espouse the use of innovative, multi-scalar research methods to advance knowledge on "societal transitions and transformation" that are just and sustainable [198].

Drawing on data from the Townsend Index score of deprivation for Local Authority Districts (LADs) in Great Britain, Roddis et al. [179] demonstrated the impacts of social capital on the community acceptance of renewable energy project siting and equity. For solar farms, a unit increase in the Townsend score – representing a more deprived area – increased the likelihood of planning approval by 15 %, while the opposite trend was reported for onshore wind applications, with the likelihood of planning approval decreasing by nearly 11 %. The authors linked these findings to the impact of social capital on planning processes, suggesting that wealthier communities consider wind farms to be a more acceptable land use than solar farms, leading to lower acceptance rates for solar projects in more affluent areas [179].

Viewed through an energy justice lens [220], these results indicate that affluent communities have greater capacity to oppose unwanted energy projects than poor communities, exemplifying a case of procedural injustice. When procedural injustice takes effect, the conditions for distributional injustice are also exacerbated, whereby material benefits, or public resources and negative externalities, are unevenly allocated [216]. Under such conditions, disparities in social capital may result in deprived areas becoming soft candidates for an influx of certain renewable energy projects [179]. Specifically, rural areas, lying beyond a thriving commuter belt and with an industrial heritage, present prime sites for RE projects due to their low landscape value [221].

3.3.3. *Temporal and socio-historical factors*

Following a case study analysis of national energy transitions in the United States (nuclear power), Brazil (sugar cane ethanol for vehicles), and Sweden (biomass fuel), Malone et al. [222] highlighted the importance of "political-social-cultural national narratives" to the technology diffusion process and socio-political acceptance. This observation can also be extrapolated to the *meso*-scale (regional/local scales) and processes of community acceptance. According to van Veelen and Hagget [223], the commonplace narrative around community renewable energy projects is that "local action can and will be effective, that communities can function as the site of cooperative action as well as being the recipient of collective benefits." Whether such a notion comes to fruition is deeply entrenched in the pervading history and culture of the community in question, wherein energy futures become shaped by the totality of multiple and often competing place identities and place attachments, both at the community and individual level [223]. As discussed here through examples of industrial towns, past energy cultures may be sources of pride and joy, or trauma and stigma, but usually prove difficult to categorize in overtly binary terms.

Engaging with the theme of stigma in the UK context, Parkhill et al. [224] highlighted how historical associations of "risk and threat, pollution and dirtiness" are especially pronounced in the case of nuclear and coal-fired power stations, and more recently fracking [225]. Despite strong political backing, public support for fracking decreased between 2014 and 2018, with a mean score of just 22 %. This rating was significantly lower than the next most unpopular energy technology, nuclear power, which had a mean score of 37 % between July 2012 and April 2018 [131]. Short et al. [226] suggest that public resistance originated and subsequently escalated due to a "collective trauma" being inflicted on communities in the North of England during the planning process. The "stigmatization effect" [225] was further amplified by risk perceptions concerning drinking water, environmental degradation, and distributional injustice [227]. Prolonged procedural and distributional injustice [227] resulted in widespread public distrust, leading to sustained, active resistance across Lancashire [226,228] throughout the 2010s and arguably, de facto national opposition to fracking [131]. Nevertheless, it took until 2019 for the UK government to impose a moratorium on the technology, which was seen by many as act of political opportunism [225]. These findings serve as a case in point of the potentially far-reaching implications of historical associations and recent environmental legacies, albeit in a non-renewable energy context. Furthermore, the case of fracking in Lancashire and moreover, the legacy left behind by coal mining demonstrate the scope for enacting restorative justice.

At one extreme, stigma and trauma may lead to strong community opposition, however, these same inflictions may also numb deprived or geographically vulnerable communities from the potential adverse impacts of energy activities to some degree [229]. At the same time, it should be borne in mind that deprived communities often have muted voices as stakeholders [230], reflecting a tendency towards procedural injustice. Interestingly, examining the controversial aspects of renewable energy siting, van der Horst [221] reported that communities with an industrial legacy or mining history are more attuned to the reality that electricity comes from a production site and involves complex transportation networks and storage activities. Such communities may be more acute to recognizing the "embedded" [231,232] or "invisible" [233] nature of electricity consumption, whereby consumers are increasingly distanced from modern production sources [234]. Given this attunement, people in communities associated with a legacy of heavy industry and subsequent pollution and stigmatization, such as Teesside in the North East of England [230], may have higher tolerance for the potential negative impacts of energy generation than residents in wealthier communities [221]. Notwithstanding, such communities remain more likely to welcome energy projects that reduce social and environmental blight [229].

In this sense, there is a certain paradox at play regarding the thresholds and desires of people living in areas characterized by a legacy of social deprivation and environmental degradation. Further illustrating this argument, proposals for onshore wind farms in the early 2000s near the Corus steelworks in Teesside, and Goole in Yorkshire, were largely welcomed by locals due to positive perceptions of economic

[10] SDG7 aims to "ensure access to affordable, reliable, sustainable and modern energy for all.'.

benefits [235]. In the Yorkshire case, the importance of socio-economic factors was especially pronounced in the community of Old Goole, the nearest village to the windfarm site.[11] By contrast, Haggett [177] described how a proposal for an offshore wind farm located off the coast of Teesside sparked somewhat unexpected resistance from protestors advocating for the rights of people living near hazardous industry.

Such case studies suggest that communities characterized by an industrial past may sometimes rally to protect those areas yet to be spoiled by polluting activities [177], as opposed to passively accepting proposed socio-economic benefits. While environmental issues, especially concerning air pollution and water contamination present potential grounds for community resistance to energy developments in deprived areas, there is usually greater scope for opposition when projects fail to prioritize employment opportunities for the local community [177,230]. Critically, when considering community acceptance, the cost-benefit and risk perceptions side of energy projects should be examined within the broader context of temporal and socio-historical factors, and related energy cultures.

3.3.4. The social acceptance matrix

A focal point of recent social acceptance research builds off the recognition that many studies have lacked a sound theoretical or conceptual foundation [180]. For example, reviewing 132 publications on acceptance studies regarding the impacts of renewable energy projects on land use, Busse and Siebert [180] found that only one-third of researchers adopted a theoretical approach in their studies. This deficit has resulted in conceptual 'fuzziness' [181] by failing to reflect the multidimensional, co-evolving nature of social acceptance and the interrelations between its key dimensions [111,236]. Consequently, a comprehensive understanding of the dynamics of social acceptance remains 'elusive' [111] and challenging [98], with several analytical areas in need of further exploration [48].

This elusiveness is strongly rooted in terminological ambiguity, owing to range of similar terms that can be easily misconstrued given that the boundaries of interchangeability are poorly defined [161]. When examining how the public perceives new energy technologies, 'social,' 'societal,' and 'consumer' acceptance are some of the common terms adopted by researchers. However, such concepts have been frequently applied to various phenomena with different definitions [98]. Similarly, the terms 'social acceptance' and 'social acceptability' have been used inconsistently,[12] which has led some authors to advocate for differentiating between the concepts [180,202]. In linguistic terms, L'Orange Seigo et al. [237] suggest that "acceptance refers to the act of accepting, whereas acceptability is a property of the item to be accepted." The risk acceptance literature further distinguishes between 'expressed' and 'revealed' preference [238].[13]

Compounding matters further, the study of public acceptance also includes a range of relevant terms such as "public perceptions, public opinion, public beliefs, public awareness, public understanding, social representations or risk perceptions" [111]. Reflecting this diversity, Gupta et al. [113] incorporated seven terms[14] for their key word search when reviewing the public acceptance of ten 'controversial' technologies with 'transformative' potential. Clearly, the social acceptance literature presents a distinct lexical richness owing to a plethora of relevant phrases. However, this richness is characterized by notable ambiguity, most visible in the need to distil the blurred boundaries between social and public acceptance [161].

In a recent critique of Gaede and Rowlands [46], Wolsink [76] reviewed conceptual developments in the study of social acceptance since its inception in the 1980s. In the context of studies on energy technology and fuels, he argued that public acceptance is an invalid proxy for social acceptance [76]. Acknowledging that individual acceptance has a specific 'internal structure,' "composed of attitudinal elements (attitudinal acceptance), behavioral intentions, and actual behaviors (behavioral acceptance)" [48], Wolsink [76] redefines public acceptance as "the aggregate degree of acceptance by individual citizens" according to attitudes, behaviors, and tolerance. In contrast, social acceptance "concerns not only the public, but all relevant actors, and not primarily actor positions, but processes" [76].

Although a wide range of concepts and definitions have been proposed in the literature to date, there is underlying consensus that social acceptance studies should aim to capture the multiple dimensions of technology adoption and use [46,76]. Furthermore, it has been emphasized that the interrelations between consumer values, perceptions, attitudes, behaviors, and actions should be at the forefront of such analysis [48,111]. Personal values impact "beliefs, attitudes, preferences, and norms related to environmental behavior" and other actions [52], which in turn affects consumer willingness to adopt low-carbon energy technologies.

To capture its full richness, social acceptance should therefore be viewed as "a socially constructed outcome" – as opposed to a "one-way process" of adoption or rejection of technology innovation – in which interests become "mutually aligned" [236] and complement existing socio-cultural structures [98] (see Fig. 4). Furthermore, the object of social acceptance research should be "new phenomena, new ideas, policies, and projects" [181]. This reconfiguration of the key components of social acceptance, marking an explicit distinction from public acceptance, exemplifies the self-reflective nature of third wave scholarship and the drive towards more integrated research approaches [239]. The next Section (3.3.5) further reflects on 'questionable' and 'disturbing' trends in the literature [76], foremost identified by Maarten Wolsink, and increasingly discussed by other energy transition scholars [48,62,63,114,168,180,202,203].

3.3.5. A spectrum of positive–negative and active–passive potentialities

Wolsink [76] exposed questionable and concerning trends in the literature, reflecting a tendency towards conceptual misrepresentation and simplification. Owing to a wide range of individual research perspectives [54], the term social acceptance has been used in a variety of ways and taken on different meanings according to specific cases of technology diffusion. When social acceptance towards an emerging technology has an active element, consumer responses may be 'favorable' or 'positive' [48]; transmitted through "endorsement, approval, approbation" or equivalent expressions [114]:

> Energy-technologies acceptance may be defined as an affirmative reply or a positive attitude …that is likely to lead to supporting behavior for the respective technology if necessary or requested [54].

Roche et al. [162] describe social acceptance in terms of consent or active support, which is established when multiple social interests are coordinated in a way that serves to promote the technology transition, as well as the interests of the public [98]. When this 'alignment' is reached, the significance of technology adoption and associated actions are institutionalized both within and between stakeholder groups [98]. While different meanings have been explored by some researchers, conceptualizations of social acceptance remain 'narrow' and 'problematic' within the energy transitions literature [240]. To date, only a handful of researchers have approached and understood social acceptance beyond a single discipline such as psychology, sociology, or innovation research [180], stifling the pursuit of more integrated and

[11] Citizens of Old Goole hoped the project would help bridge the economic gap with their more affluent neighbors residing in 'New' Goole.

[12] See Table 1 in [180] for a comprehensive review of definitions used in the literature.

[13] Expressed acceptance is reflected by agreeing with a statement such as "I would accept a hydrogen fueling station in my community," whereas revealed acceptance is represented through non-engagement in the activities designed to promote or prevent such a project [238].

[14] "Consumer acceptance OR consumer response OR consumer acceptability" AND "societal response OR societal acceptance OR societal concern OR social acceptability.".

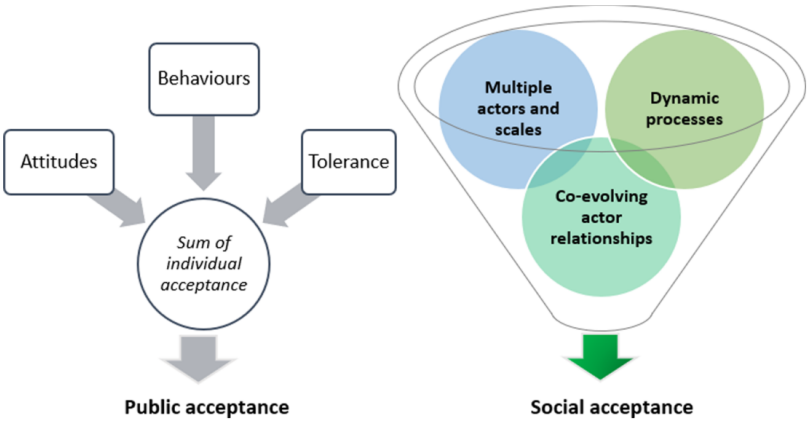

Fig. 4. The components of public and social acceptance based on [48,76].

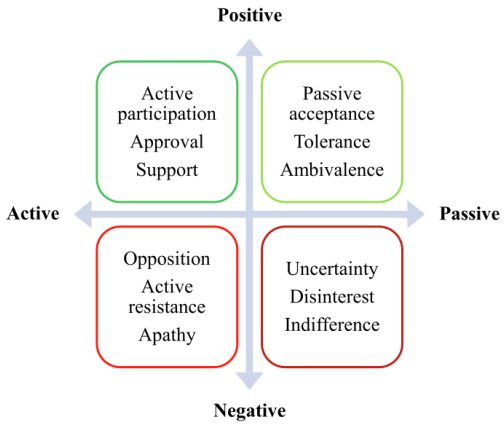

Fig. 5. The social acceptance matrix based on [48,62,63,76,114,168,203].

richer research questions [76]. As Von Wirth et al. [54] reflect, "a coherent overview of this knowledge across scientific disciplines is nonexistent."

In most studies, the term 'acceptance' reflects a passive tolerance for technology adoption [203]. Passive tolerance usually corresponds to an absence of public resistance based on perceptions of low risk levels [240]. Such representations fail to recognize social acceptance as a multi-dimensional phenomenon [48] with complex psychological components [76]; shaped by active and passive reactions to new technology, and positive and negative valuations [236,240]. As conceptualized by Schweizer-Ries [63] and expounded on by Friedl and Reichl [62], these opposites form an acceptance 'matrix', consisting of a wide 'spectrum' of potential responses (see Fig. 5) such as support, uncertainty, ambivalence, tolerance, resistance, or opposition [76,203]. Consumer responses can fluctuate freely between positive–negative and active–passive ends of this spectrum, corresponding to the adoption or rejection of new behaviors and practices [62].

This turn towards a deeper understanding of emotional responses [241] and affective evaluations [242], as captured in the social acceptance matrix, epitomizes the third wave of thinking. For example, Martiskainen et al. [243] reported that positive emotions associated with hydrogen technologies may include desire, joy, gratitude, and

Table 8
Key aims and attributes of the three waves of research on the social acceptance of RET.

	Wave 1 (~1995–2007)	**Wave 2** (~2007–2014)	**Wave 3** (~2015–present)
Approach	Normative approaches	Criticism approaches	Critical approaches
Main assumptions regarding local opposition to RET	Examining NIMBY syndromes and responses	Criticizing NIMBYism and proposing alternative theories and explanations	Focusing on how spatial dynamics, energy justice, power relations, and historical factors shape people's responses to the development and diffusion of RET
Main lines of enquiry	Characterizing opposers and supporters	Examining which socio-psychological and community factors affect opposition to RET, especially in terms of procedural and distributional justice	Adopting a critical approach at *ideological* (e.g. revealing and contesting RET as business and usual), *theoretical* (e.g. applying agonist approaches to community engagement), and *methodological* levels (e.g. using discourse analysis)
Anticipated societal implications	To overcome local opposition to RET	To understand public resistance and ease the transition to RET	To question if opposition to RET should be reduced/overcome
Examples of key studies	[119]	[110–112,145,167]	[54,61,64,76,180,181,243]

Source: Authors' compilation based on [61].

pride, while negative emotions include fear, anger, and greed. However, it should be noted that even at the dawn of Wave 1, Walker [119] had flagged how public attitudes "can be highly variable, dynamic and sometimes contradictory." In this sense, recent theoretical and conceptual advancements mark an uptake in response to an argument some three decades in the making.

3.3.6. Social acceptance as a cross-scalar and multi-actor process

Having reviewed theoretical and conceptual developments presented within the energy literature, there are a multitude of factors that shape social acceptance: legitimacy, trust, and justice [110,167,168]; socio-political, demographic, cultural, psychological, and contextual factors [52,111,240]; and perceptions of costs, benefits, and risks [112,118,156]. In sum, social acceptance is a 'complex' and 'dynamic' phenomenon [76,111] driven by a diverse range of technical, political, economic, and social factors [167]. Compared to earlier waves of research (see Table 8), studies in the third wave stress that the 'positions' of respective actors are dynamic and continuously evolving [76]. Social acceptance is a thus a process where "the question of acceptability is at stake" for each decision-maker [110] and should be examined as a 'cross-scalar' [244,245], 'multi-actor' [48] phenomenon that accounts for "the intrapersonal characteristics of individual acceptance" [54]. In response, acceptance studies should account for how society encounters technology within a unique historical, geographical, socio-cultural, institutional, and economic setting [64,80,98,168]. At the same time, attention should be also paid to whether the scale of technological change itself impacts social acceptance [246]. In view of these findings and the inherent theoretical challenges associated with the study of social acceptance to date, the remainder of the paper answers the call for a clear conceptual approach to the study of domestic hydrogen acceptance [22,42,69,247,248].

4. Social acceptance of hydrogen energy technologies

4.1. Research areas and approaches

The early scholarship on hydrogen perceptions reflects a mix of theoretical dimensions proposed in the social acceptance literature [42]. In the context of hydrogen transportation, Roche et al. [162] identified three main approaches taken by researchers: general attitudinal surveys; non-market economic valuation studies; and risk perception studies. Additional methodological approaches that fall outside these categories include studies based on semiotic theory [162], and experimental or activity analyses [249]. Scott and Powells [22] also classify the hydrogen acceptance literature into three 'strands' of studies: hydrogen for transportation; consumer willingness to pay more to support the introduction of hydrogen technologies[15]; and consumer perceptions of risk and safety.

Most acceptance studies have focused on transport, with primary interest in hydrogen-powered buses, cars and refueling stations, and some emerging interest in hydrogen-fueled shipping and aviation [70]. Hydrogen acceptance has been examined through a socio-technical lens, with several survey studies on hydrogen fuel-cell vehicles and related infrastructure, carried out in countries such as the UK, USA, Netherlands, Germany, Spain, and Japan [57,70]. In general, public support for hydrogen technologies appears to be somewhat positive yet largely reserved, owing to limited awareness and moderate concerns about safety [162]. Reviewing the literature on hydrogen as an energy carrier in transport, Hujits et al. [250] concluded that social acceptance is unlikely to be a major barrier for deploying hydrogen buses, highlighting a potential divergence between public and consumer-facing technologies. In line with the criticism approach, the study highlighted the importance of technology, location, and other contextual specific factors. Notably, prior knowledge also has been shown to act as a driver of hydrogen acceptance [251], especially in the context of transportation [252].

Broadly, this early wave of hydrogen acceptance studies [253–257] – based on both assessments of measured knowledge [253,255], and the effect of information provision [256,258] – suggested that men, younger people, the highly educated, and those in full-time employment are more likely to be better informed about hydrogen technologies than other socio-demographic groups. Furthermore, hydrogen acceptance appears to be positively correlated with environmental awareness [133,253,257] and trust in technology [256], while men are typically more supportive than women [254,257].

4.2. Factors of hydrogen acceptance

Reviewing the social acceptance of low-carbon heating solutions based on a *meta*-analysis of European projects, Heiskanen et al. [98] suggested the following factors as the key determinants of hydrogen acceptance: its characteristics in terms of safety, cost, usability, convenience and (thermal) comfort; the national and local context; the robustness of supply chains and skilled technicians; and the composition of stakeholder engagement. Capturing the complexity and interrelatedness of social acceptance, scholars have theorized that support for hydrogen energy technologies may depend on socio-economic, demographic, geographic, situational, psychological, cultural, and knowledge-related factors [98,112].

Working with several focus groups across the UK, Flynn et al. [150] showed that motivation to adopt hydrogen technologies is strongly linked to economic considerations, usability, convenience, safety, and environmental benefits. Based on a review of seven hydrogen studies, Gupta et al. [113] found that *attitude* (positive and negative), *technology characteristics*, *individual differences* (i.e. socio-economic and demographic factors), *perceived benefits*, and *knowledge* ranked as the key determinants of social acceptance. Anticipating the shift from criticism to critical approaches, Heiskanen et al. [98] linked hydrogen acceptance to the "historical and accumulated experiences" of comparable renewable energy projects, while Flynn et al. [150] argued that hydrogen-fueled technologies must align with established socio-cultural practices and socio-political views.

Subsequent studies in the UK have echoed the importance of these factors. For example, Fylan et al. [75] identified six themes reflecting the public's main uncertainties and concerns: the justification for a hydrogen conversion; the source of hydrogen and its production methods; cost factors; safety factors; practicalities; and the time scales and unknowns involved in the conversion; and behavioral factors such ease of operation and thermal comfort. To better understand hydrogen acceptance, recent studies have further examined attitudinal and behavioral factors [23], together with safety perceptions, economic factors, user experience and technical support, stakeholder engagement, and public trust to understand hydrogen acceptance [23,41,59]. Researchers in Australia have also explored similar themes and reported similar findings [69–70,72,247,248]. While early strides have been taken, more insights are required to better understand the determinants of social acceptance for hydrogen technologies across the transport, power and residential sectors, and the interrelation between key psychological, demographic, situational and knowledge-related variables [250].

4.3. The social acceptance of domestic hydrogen

Research on the social acceptance of domestic hydrogen for heating and cooking applications remains largely underexplored by energy scholars [41]. The hydrogen literature has mostly focused on its use for transport and related infrastructure [178], leaving a significant research gap for understanding the social acceptance of stationary applications

[15] These studies usually employ econometric methods such as Willingness-to-Pay (WTP) and Contingent Valuation Method (CVM).

Table 9
Summary of UK hydrogen trials.

	H21	HyDeploy 1&2	Hy4Heat	H100
Project lead	Northern Gas Networks (NGN)	Cadent Gas	Department of Business, Energy & Industrial Strategy (BEIS)	SGN
Funding mechanism(s)[1]	NIC and NIA	NIC	NIC	NIC, Scottish Government, and UK Gas Distribution Networks (GDNs)
Duration	Jul 2018–Dec 2021	Apr 2017–Mar 2023	Nov 2017–Mar 2021	Apr 2021–Mar 2027
Hydrogen scale	100 % conversion	20 % blending	100 % conversion	100 % conversion
Social acceptance context	Dimension of social science research	First demonstration of hydrogen use (2018); first public demonstration of hydrogen use (2020)	Engagement regarding home conversion	Engagement with host site

Source: Authors' compilation based on [270,314–318].
[1] The main funding mechanisms for these projects is via two pathways: (1) the Network Innovation Competition (NIC) in which gas network companies compete for higher levels of funding from energy regulator, Ofgem, to develop and demonstrate new technologies; and (2) the Network Innovation Allowance (NIA), which allocates funds directly to gas networks for smaller projects [105].

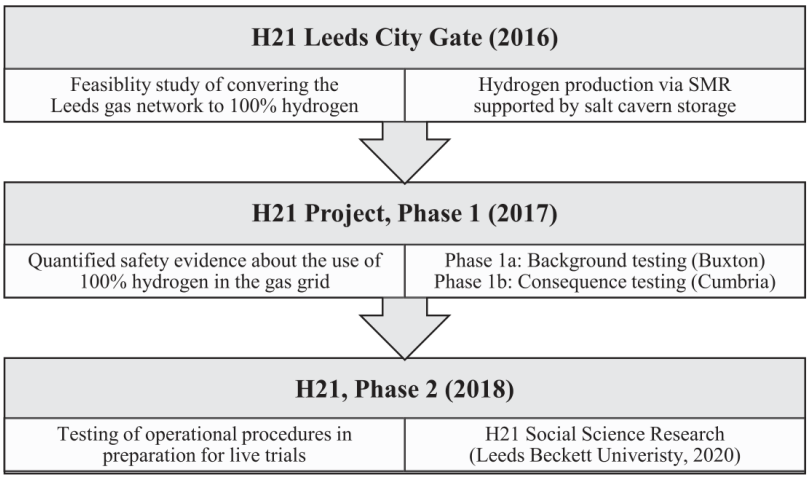

Fig. 6. Timeline and details of H21 Leeds City Gate project [75,262,263].

for the home such as hydrogen boilers and hobs [22,68]. This scarcity is reflected by hydrogen's status as a niche technology in the early stages of development and innovation [259], with few pilot projects or relevant case studies for commercial applications [178]. This point is especially true for domestic heating, which is characterized as "a new and untested proposition" [59]. By contrast, hydrogen fuel cell technology has a long history spanning two centuries [260], with ongoing efforts to deploy fuel cell electric vehicles (FCEVs) in recent years [261]. To date, few survey studies have focused on the social acceptance of domestic hydrogen [247]. Most of the existing research is limited to the UK context [22,23,41,42,59,73,75], reflecting activities around four key projects: H21, and its sub-project Hy4Heat, HyDeploy, and H100 (see Table 9).

4.3.1. *H21 Leeds City Gate: Converting the gas network to 100 % hydrogen*

The first feasibility study on domestic hydrogen can be traced back to the H21 Leeds City Gate study in 2016. On behalf of Northern Gas Networks (NGN), Sadler et al. [262] set out to determine the feasibility of converting the Leeds gas network to 100 % hydrogen. In 2017, the H21 project secured £9m of NIC funding to make the safety case for hydrogen [263] (see Fig. 6). As part of the H21 evidence base, Fylan et al. [75] conducted an online survey (N = 1027) representative of the first areas to be converted to hydrogen homes, which included Leeds, Monmouthshire, and Birmingham. This selection mirrors the unique spatial dynamics of the hydrogen transition, reinforcing that social acceptance studies should account for the corresponding geographic and community context [57]. The results indicated the scope of the emerging social acceptance matrix for domestic hydrogen, spanning responses such as acceptance, cautious support, disinterest and skepticism, reluctance, and rejection [75].

4.3.2. *HyDeploy blending trials and community trials*

Hydrogen blending – the injection of small quantities of hydrogen into the existing natural gas grid [42] – has been promoted as a 'practical' and 'non-disruptive' pathway towards securing emissions reduction in residential heating [264]. As a transition mechanism, the government is considering injecting hydrogen (20 % by volume) into the natural gas grid to help reduce short-term carbon emissions [12], which is expected to strengthen the foundations for a future hydrogen economy [265]. The first hydrogen blending trial took place on the Keele University private gas grid in Staffordshire, whereby 20 vol% hydrogen was injected successfully without compromising safety standards or modifying household appliances [41,266] (see Fig. 7).

Subsequently, HyDeploy Phase 2 was launched to extend the evidence base for hydrogen blending by moving the trials to public networks situated in the North East and North West of England [41]. This

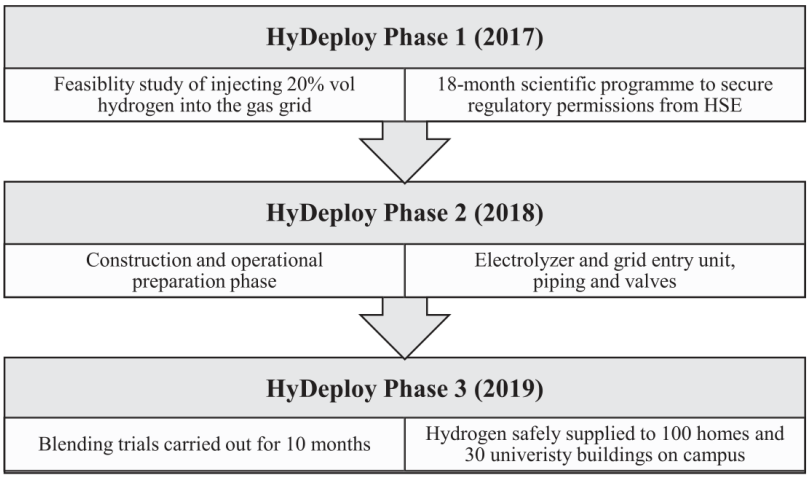

Fig. 7. Timeline and details of the HyDeploy project [41,266,297].

phase delivered its aim to "bring hydrogen injection to the same level of regulatory approval as biomethane injection" [266], through a trial of 670 houses, as well as a church, primary school, and several businesses in Winlanton, Gateshead [267]. In parallel, Scott and Powells published three studies on hydrogen acceptance in relation to HyDeploy (see Table 10), which included an online survey (N = 700) focused on the North of England [42]; a region representative of the HyDeploy trial areas and characterized by "uneven economic and social geographies" [22]. Reflecting the relevance of SPT to the study of social acceptance, the authors argued that the "analytical focus" should be shifted to capture how people are likely to behave, as opposed to what they may think or feel" [22].

Hydrogen pilot projects such as HyDeploy are critical to raising public awareness and increasing trust, while demonstrating the safety case and technical feasibility of domestic hydrogen. At NGN's Low Thornley site near Gateshead, boiler manufacturers Baxi Heating and Worcester Bosch, with support from Cadent Gas and the Department for Business, Energy & Industrial Strategy (BEIS), are showcasing their respective hydrogen heating technologies in two semi-detached modular homes [268]. The Hy4Heat project (part of H21) is the first of its kind, allowing members of the public to interact with hydrogen-fueled appliances to see how they function in comparison to natural gas appliances [268]. Test sites of this description are a critical step to providing information on aspects of behavioral acceptance, which to date has been limited mostly to the results of Scott and Powells [22].

Scaling up from activities at Low Thornley, the H100 Fife project led by SGN[16] is the world's first community trial of green hydrogen [269]. Following the literature review and focus group study commissioned by BEIS on a hypothetical hydrogen trial [59], the trial offers an opt-in process to enable around 300 homes in Levenmouth to switch their gas supply to hydrogen produced via electrolysis from Scottish offshore wind power [270]. The pre-study confirmed that "there is a strong human and social dimension" to converting households to hydrogen, which given the diversity of the UK housing stock and associated social grades, creates a wide range of potentially incompatible individual and communal needs [59]. Together with the logistical challenges of replacing appliances,[17] there is a need to integrate social, cultural, and psychological factors into the planning mechanisms of community trials.

4.3.3. Governance aspects of the UK domestic hydrogen transition

At present, a distinct set of policy, industry, and business actors are spearheading hydrogen development and deployment [179], composed of the companies who own and manage the UK's national and regional Gas Distribution Networks (GDNs), government actors such as the BEIS, boiler manufacturers, and industrial and business players, including members of the Hydrogen Taskforce, a coalition of the hydrogen industry's largest organizations [271]. UK homeowners may be quite familiar with their boiler manufacturer and energy supplier; however, most domestic energy users are unlikely to know much about the operations and territories of GDNs. Bridging this knowledge gap may prove critical to decarbonizing residential heating, since GDNs are the primary group driving innovation in network management and current R&D activities, in turn influencing the spatial dynamics of early hydrogen development and deployment across the UK (see Fig. 8).

Regarding trust in GDNs, Scott and Powells [41] caution that survey participants in the HyDeploy demonstration project raised concerns about the underlying motives of the gas industry, as well as the central government. Demski et al. [175] also found that the UK public considered energy companies as accountable for helping to lead the energy transition, but viewed their contribution to date as insufficient, especially given their ability to invest sizeable capital in low-carbon energy infrastructure and technologies. Evensen et al. [272] further highlighted that public willingness to help fund the energy transition rests strongly on perceptions of procedural and distributional justice regarding the role of government and energy companies.[18]

Based on the literature review findings, citizens appear willing to trust in gas companies in terms of providing safety and risk management, reflecting a degree of socio-political acceptance. However, consumers lack confidence in the commitment and ability of the same

[16] Formerly, Scotia Gas Networks, Scotland Gas Networks and Southern Gas Networks.

[17] For a detailed discussion of these logistics, see [25].

[18] Respondents assigned most responsibility to energy companies (45%), followed by the government (32%).

Table 10
Studies on the social acceptance of domestic hydrogen in the UK, 2018–2020.

Study	Location, research type, and sample size	Approach and research scope	Findings
[23]	a) Nationally representative online survey UK; N = 1029 b) Four focus groups London and Edinburgh; N = 29	• Assesses the public acceptability of hydrogen heating, relative to that of heat pumps	• Knowledge and awareness of both technologies is low • Preferences depend mainly on how respective advantages and disadvantages are communicated
		• Examines household preferences and barriers to consumer acceptance, with a focus on attitudinal differences between socio-demographic groups[1]	• 45–55 % of respondents had no clear preference towards either hydrogen heating or heat pumps throughout most stages of the surveyAt the end of the survey (stage 6), • 63 % of consumers expressed a preference for heat pumps • Hydrogen boilers had a higher perceived installation burden
[59]	4 focus groups with consumers from different housing segments connected to the gas grid[2] England: Manchester and Birmingham; N = 39	• Assesses consumer perspectives on the disruption and costs impacts of a hypothetical hydrogen conversion trial for approx. 300 homes[3]	Skepticism, concerns, and doubts regarding several key areas: Potential cost-neutrality of the hydrogen trial Benefits of the switchoverThe duration of the switchover period (3–4 days)
		• Focuses on logistical and welfare issues, stakeholder groups, and how participation and communication can be promoted	Disruptive impacts Adequacy of proposed incentive schemes and/or compensation packages Loss of equivalence compared to natural gas
[41]	Nationally representative online survey UK; N = 742	• Designs and deploys an online survey,[4] collecting quantitative data on public perceptions of hydrogen and hydrogen blending	• Public knowledge and understanding of hydrogen are low • Neutral perceptions of hydrogen's suitability for the domestic environment
		• Based on initial perceptions, values, and knowledge of hydrogen; the possibilities and pitfalls of hydrogen blending; public trust; and participants' overall support for hydrogen	• Support levels increased when participants were informed about hydrogen's environmental benefits • Perceived cost proved the most significant barrier to social acceptance
[22]	Paper-based survey and in-person interviews (cafés/coffee shops) 10 different locations in the North East of England; N = 100	• Adopts a SPT approach[5] and employs a 'talking' methodology	• Cooking practices more likely to be disrupted than heating practices die to hydrogen's flame characteristics (i.e. near invisibility)
		• Examines how the physical and chemical properties of hydrogen may impact the 'gas-energized' social practices of cooking and heating	• Most participants envisaging hydrogen bringing positive environmental benefits, without compromising safety and user experience, or hampering the economy • It is imperative to develop a suitable colorant for hydrogen-fueled appliances
[42]	a) Online survey, representative of the HyDeploy2 trial areas North of England; N = 700 b) Paper-based survey conducted in cafés Nine towns in the North of England; N = 102	• Employs a mixed methods approach – integrating spatial, quantitative, and qualitative analysis based on the principles of 'grounded theory' [319,320]	• Respondents were concerned that hydrogen could increase their energy bills and/or taxes, and exacerbate existing problems of fuel poverty • Acceptance is likely to hinge on what hydrogen can deliver to the local community in terms of social and economic benefits
		• Elicits and evaluates public perceptions of hydrogen and hydrogen blending in the UK, in relation to theories of social practice, energy justice, and place attachment	• The transition is set to engender complex and unpredictable disruptions and enhancements to people's feelings of place attachment
[75]	Nationally representative online survey UK: Leeds, Monmouthshire, and Birmingham; N = 1027 b) Discovery interviews N = 12 c) Deliberative workshops[6]	• Explores public perceptions of changing the domestic fuel supply to 100 % hydrogen	• 28 % of respondents supported changing to hydrogen gas and using it for heating and cooking
		• Examines beliefs about the environment, inconvenience and costs, safety, and potential economic impacts	• 20 % were more cautious about the use of domestic hydrogen and concerned about potential disruptions • 30 % were disinterested in and skeptical of the hydrogen conversion due to underlying uncertainties and information gaps • 10 % were unconvinced about the conversion • 12 % rejected it outright

Source: Authors' compilation, adapted from [43].

[1] Technical stimulus materials were developed to explain the heating technologies in simple terms, using real life scenarios, while attitudinal differences between demographic groups were gauged according to housing tenure, level of education, location, and age.

[2] Two with owner-occupiers, one with private landlords, and one with a mixture of tenants.

[3] The conversion scenario required no financial investment from households. Although participation was mandatory, households could choose to op-out by disconnecting from gas and switching to electric heating. After the trial, a decision would be made about whether the community would use hydrogen or natural gas.

[4] Based on a review of existing academic and policy literature on the public acceptance of renewable energy and hydrogen technologies.

[5] Participants were provided with simple pieces of information regarding the material and socio-technical properties of hydrogen and asked how these properties might impact their existing hob and boiler practices.

[6] Assessed the public's ability to understand and communicate information about the hydrogen transition.

companies to promote community engagement and trust, through transparent and participatory planning processes [43]. This is reflected by an underlying sense of skepticism or uncertainty regarding the actions of both the gas industry and government, in part owing to poor reputation linked to past policy and business failures [41,59,73,74]. Such a situation undermines the potential for "strong socio-political acceptance," [54] which is critical to "implementing innovations" [97], and supporting community acceptance through trust mechanisms [172,273] and participatory processes [274,275].

Alongside the government, the role of the gas industry in managing a just transition cannot be overlooked, especially since community acceptance is likely to hinge on the level of disruption associated with changes to pipework and other infrastructural upgrades at street level, and how these disruptions are communicated and justified [23,59]. Critically, GDNs, together with energy suppliers, will need to pay careful attention to how they plan, promote, and execute roll-out strategies to secure trust and fairness throughout the hydrogen transition, which should also be enshrined in policymaking. Building off these findings, Section 5 fulfils the main research objective by conceptualizing the social acceptance of domestic hydrogen.

5. Conceptualizing the social acceptance of domestic hydrogen

5.1. Defining the triangle of social acceptance for hydrogen households

If hydrogen homes are to become a reality, the technology will need to secure socio-political, community, and market acceptance from end-users, which represent co-evolving layers of social acceptance. First, it must be clarified what these dimensions mean for prospective hydrogen-fueled communities and households. This calls for clear understanding of the main actors and factors connected to each acceptance dimension (see Table 11).

Underpinning the potential for macro-scale transformation, *social* and *political factors* determine the conditions for technology development and diffusion. **Socio-political acceptance** centers on whether consumers perceive domestic hydrogen as a legitimate and just technology pathway for increasing social, economic, and environmental benefits. A favorable socio-political environment can be supported through commitment to a robust hydrogen strategy and clear targets. Following on from the UK Hydrogen Strategy, supported by the Heat and Buildings Strategy, and the British Energy Security Strategy, the government and key stakeholders should work towards facilitating adequate institutional and regulatory frameworks aligned to the net-zero and energy poverty agendas.

The potential for a socially acceptable transition to hydrogen homes will also be shaped by the level of **community acceptance**, which may depend on a wide range of *contextual factors* such as location, history, and heritage. Operating at the *meso*-level, community acceptance is needed at the outset to help facilitate local trials, infrastructural changes, and other physical measures for enacting a national hydrogen strategy. To reinforce both socio-political and community acceptance, the strategy should pledge long-term benefits to local communities where hydrogen is being deployed, especially in terms of employment opportunities and income security. Such deliverables should be clearly communicated to citizens during the planning process to ensure procedural justice and greater potential for restorative justice in historically deprived and degraded areas. At a later stage in the transition process, local communities and households must be willing to accept, or at least tolerate, the potential disruptive impacts associated with the conversion process. These disruptions will include infrastructural changes and operational activities at street level, as well as temporary disconnection from the gas grid and engineering activities within properties.

Finally, **market acceptance** for domestic hydrogen depends on the role of investors, industry and business actors, manufacturers, installers, and other intermediaries. Should these key actor-networks prove successful in driving low-carbon hydrogen production, while establishing an effective marketplace through robust supply chains and strategic investments; consumers must then be willing to invest in new appliances to actualize market acceptance. At the household level, market acceptance rests on whether consumers perceive domestic hydrogen as a 'like for like' replacement for natural gas [276], with willingness and ability to invest in or modify appliances, and to absorb related energy costs [43]. Together with the purchasing of hydrogen-fueled appliances, skilled technicians are needed to secure market confidence. Driven largely by *economic* and *socio-demographic factors*, market acceptance is critical for reinforcing socio-political support at the macro-economic level and financial investments at the *meso*-scale, alongside hydrogen adoption at the micro-level. All three scales hinge firmly on the cost-competitiveness of hydrogen. In the case that consumers should prove unwilling to invest in new appliances, the large-scale market introduction of hydrogen heating would likely require a more top-down, state-led approach, comparable to historical transitions to natural gas in the UK [277], Netherlands [278], Greece [279], and other countries.

Having defined each acceptance dimension and following the findings presented in Table 3, Table 11 extends the analysis with an overview of the main actors and factors shaping domestic hydrogen acceptance in the UK context. This addition reinforces the multi-dimensional and multi-scalar nature of social acceptance, and the diversity of key stakeholders and actors.

5.2. Attitudinal and behavioral dimensions of hydrogen acceptance

In presenting the main actors and driving factors linked to socio-political, community, and market acceptance, Table 11 reveals that three dimensions are insufficient for capturing the full breadth and unique configuration of social acceptance for hydrogen homes. This conclusion follows the turn from criticism to critical approaches, with domestic hydrogen studies attributing significant weight to the importance of attitudinal and behavioral acceptance factors (see Table 12). Notably, the behavioral dimension of the energy transition has often been overshadowed by a stronger focus on socio-political, community, and market aspects of renewable and low-carbon technologies.[19] While these dimensions remain critical to understanding social acceptance, technologies that are designed to permeate the domestic environment such as hydrogen boilers and hobs must be thoroughly understood in view of consumer attitudes and behaviors. As key determinants of individual acceptance [48,52,111,152], the inclusion of attitudinal and behavioral dimensions shifts the focus more directly to the micro-scale, wherein the market adoption of low-carbon household technologies is ultimately realized [55,281]. At the outset, constructing a valid framework calls for a distinction to be made between "beliefs or attitudes" and "actions or behaviors" [111].

Attitudinal acceptance depends on how public perceptions of domestic hydrogen are shaped by knowledge and awareness, which is influenced by *socio-psychological factors*. The emergence of attitudinal acceptance resounds with the establishment of cognitive legitimacy [282], enabling consumers to know and appreciate hydrogen-fueled appliances first-hand, which advances incorporation and conversion within the domestic environment [86,87].

Behavioral acceptance is determined by *socio-cultural factors*, resting on how consumers perceive the impacts of domestic hydrogen adoption on aspects of the "lived experience" of heating [283] and cooking [22], such as performance, functionality, comfort, safety, and disruption [23]. Firstly, households must be willing to tolerate the potential disruptive impacts and the overall installation burden associated with the conversion process itself.

[19] A case in point is the rise of public opposition, local resistance, political U-turns and planning constraints regarding the siting of onshore wind farms in the UK and other European countries such as Germany and Denmark [280].

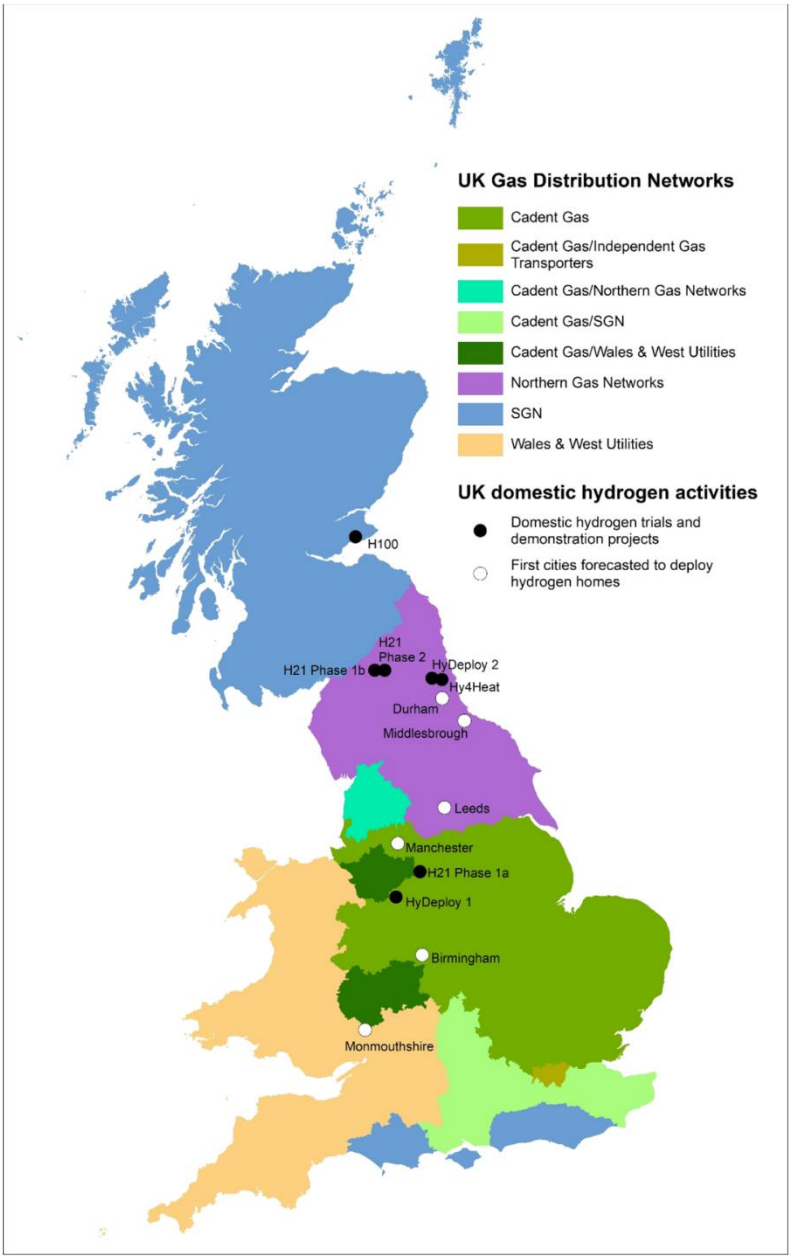

Fig. 8. UK domestic hydrogen activities by territories of Gas Distribution Networks.

Table 11
Actors and factors behind social acceptance of domestic hydrogen.

Acceptance dimension and significance to consumers	Actors	Factors
Socio-political		**Social and political**
Do consumers perceive domestic hydrogen as a legitimate and just technology pathway for increasing social, economic, and environmental benefits?	• Central government	• Public views on national priorities
	• Committee on Climate Change (CCC)	• Trust in the government's net-zero and energy poverty agenda
	• Department of Business, Energy & Industrial Strategy (BEIS)	• Impacts on energy/fuel poverty
	• Health and Safety Executive (HSE)	• Net economic impacts
	• Gas Distribution Networks (GDNs)	• Scope of industrial regeneration
	• Media	• Trust in evidence and information provided by political parties and other key stakeholders
	• General public	• Public perceptions of hydrogen production and distribution methods
		• Scope of community trials and demonstration projects
Community		**Contextual**
Do consumers perceive the local impacts of the switchover as tolerable or acceptable, with the transition securing long-term benefits for their local communities?	• Local government officials	• Trust in local government and supply chains
	• Local councils	• Perceptions of the safety and suitability of hydrogen storage
	• Supply chains	• Distribution of costs and benefits
		• Place attachment and historical heritage
		• Disruptions caused by the switchover at street level
		• Nature of communication processes
		• Level of community engagement
	Residents	• Socio-economic benefits linked to employment opportunities and community development
Market		**Economic**
Are consumers willing and able to invest in modifying or purchasing heating and/or cooking appliances; and to absorb potentially higher energy costs if gas bills increase?	• Hydrogen producers and distributors	• Costs of hydrogen production
	• Investors	• Cost of appliance upgrades
	• Gas companies	• Fuel/energy costs
	• Boiler manufacturers	• Impacts on property prices and rents
	• Gas engineers and technicians	• Financial impacts on households with home-based employees
	• Homeowners	• Incentive schemes and compensation packages
	• Tenants	• Maintenance and repair requirements
		• Alternative technology choices

Source: Authors' compilation based on [22,23,41,42,59,75].

Table 12
Attitudinal and behavioral factors of domestic hydrogen acceptance.

Attitudinal factors	Source(s)
• Safety perceptions	[22,23,41,42,75]
• Environmental values and awareness	[22,23,41,75]
• Knowledge and understanding of hydrogen as a fuel and technology	[41]
• Knowledge of hydrogen production methods	[75]
• Feelings associated with the word hydrogen	[41]
• Perceptions of climate change	[75]
• Perceptions of impacts of hydrogen appliances on heating/cooking performance and efficiency	[42]
• Perceived costs, benefits, and risks	[23]
• Role of information provision	[2,–23,41,42,59,75]
Behavioral factors	
• Impacts to the lived experience of heating and cooking (i.e. boiler and hob practices)	[23,59,75]
• Disruptions to daily routine and overall burden of installation	[23,59,75]
• Perceived impacts on home appliance use	[41,42]
• Maintenance and repairs	[59]

Source: Authors' compilation.

5.2.1. Socio-political, cognitive, and socio-cultural legitimacy

Social acceptance is strongly linked to the overall legitimacy of a given technology, which according to Aldrich and Fiol [282] has two distinct categories, namely socio-political and cognitive legitimacy. Socio-political legitimacy depends on the extent to which key stakeholders recognize the suitability of a new technology according to existing social norms and laws. In contrast, cognitive legitimacy operates on the consumer level, emerging as end-users become better informed and more knowledgeable about a new technology until it is incorporated and converted [88,89]. It follows that cognitive legitimacy is a precondition for facilitating socio-political legitimacy, since acceptance of a new technology by key stakeholders and the possibility for active participation and cultural adoption can only ensue following the spread of knowledge [282,284]. While socio-cultural norms influence public perceptions, socio-political legitimacy will be undermined when these perceptions are at odds with the perspectives of technical experts and policymakers [285].

To this line of thinking, a third dimension can be added, namely, 'socio-cultural legitimacy.' Behavioral acceptance – understood through the lens of social norms, intentions, habits, and actions [282] – calls for socio-cultural legitimacy, in the sense that hydrogen must align predictably to the established social practices of (natural) gas heating and cooking [42]. On one level, this means ensuring that the sensory experience of hydrogen provides a continuum to the lived experience of domestic energy in the UK context. In turn, technical solutions to hydrogen odorization and flame coloration [24,38] should minimize disruption to the socio-material nature of boiler and hob practices [22]. At an overall level, socio-cultural legitimacy rests on the extent to which

hydrogen is viewed as a direct substitute for natural gas in terms of safety and performance of appliances [59,276], coupled to the critical benefits of energy efficiency, energy security, and decarbonization [28].

At the positive and active end of the social acceptance matrix, once cognitive legitimacy is firmly in place, the uptake of new socio-cultural values such as environmental citizenship [150,201] and energy-saving attitudes [286,287] may have a transformational impact on the diffusion of low-carbon domestic hydrogen. Accordingly, social acceptance rests on two additional questions concerning consumer attitudes and behaviors:

(1) **Attitudinal**: According to knowledge and awareness levels, do consumers perceive domestic hydrogen as a safe, reliable, efficient, and clean technology option, offering at least general equivalence to natural gas in terms of use and performance?

(2) **Behavioral**: Are consumers willing to tolerate potential disruptions to their domestic environment and daily routine during the switchover, and subsequent changes to the lived experience of heating and cooking?

5.3. Linking the five dimensions of domestic hydrogen acceptance

To facilitate a socially acceptable and efficient transition to domestic hydrogen, there should be a clear definition of what social acceptance means to different households and communities in the national context, accounting for the importance of geographical scale, household composition, housing tenure, and other key spatial and socio-demographic factors. As argued throughout this paper via the lens of social acceptance issues [54,110], the spatio-temporal patterns of renewable energy adoption [288] are shaped by a range of interacting scales, dimensions, and factors.

Synthesizing the theoretical, conceptual, and empirical findings, together with the results presented in Table 11 and Table 12, suggests that hydrogen acceptance is a co-evolving phenomenon rooted in the dynamic interplay of at least five distinct dimensions: socio-political, market, community, attitudinal, and behavioral acceptance (see Fig. 9). These dimensions should be regarded in one sense as distinctive building blocks for establishing social acceptance, but moreover as interacting layers that co-evolve over time within a heterogenous system. This co-evolution unfolds as consumers shift between positions of ignorance, resistance, indifference, ambivalence, tolerance, and acceptance, according to a wide range of socio-political, contextual, socio-psychological, socio-cultural, economic, and socio-demographic factors. This conceptualization unifies both criticism and critical approaches to the study of social acceptance, thereby closing the knowledge gap on the domestic hydrogen transition.

Attitudinal acceptance can be regarded as a foundation for encouraging households to adopt hydrogen, which is required to ensure that consumers accept the risks, benefits, and costs of the transition. If knowledge and awareness levels are lacking to an extreme, there is limited feasibility that consumers would take strides to actively support domestic hydrogen adoption. At present, the social acceptance of domestic hydrogen remains constrained by uncertainty about how its costs, benefits, and risks compare to other low-carbon heating technologies, such as heat pumps and district heating [23]. Previously, it has been shown that awareness is a precondition for the large-scale adoption of innovative, low-carbon technologies, which calls for easy access to reliable sources of information [151]. Domestic hydrogen is expected to follow suit in this regard. Thus, moving from tolerance/passive acceptance to active support, calls for sustained consumer engagement, which rests heavily on the efficacy of communication channels such as media representations and local councils. Furthermore, the potential scope of consumer engagement will be driven by the results of forthcoming trials and demonstration projects [289,290], as reflected by Cadent's "Green Print" for a low-carbon future: "the challenge of decarbonizing heat will require consumer engagement and consent on a scale we have not yet achieved in energy – and perhaps in any sector" [291].

In this sense, attitudinal acceptance underpins the scope for broader public support across the macro-level, serving to consolidate the level of consumer buy-in regarding the legitimacy of hydrogen, as a net-zero technology aligned to strengthening energy security and alleviating

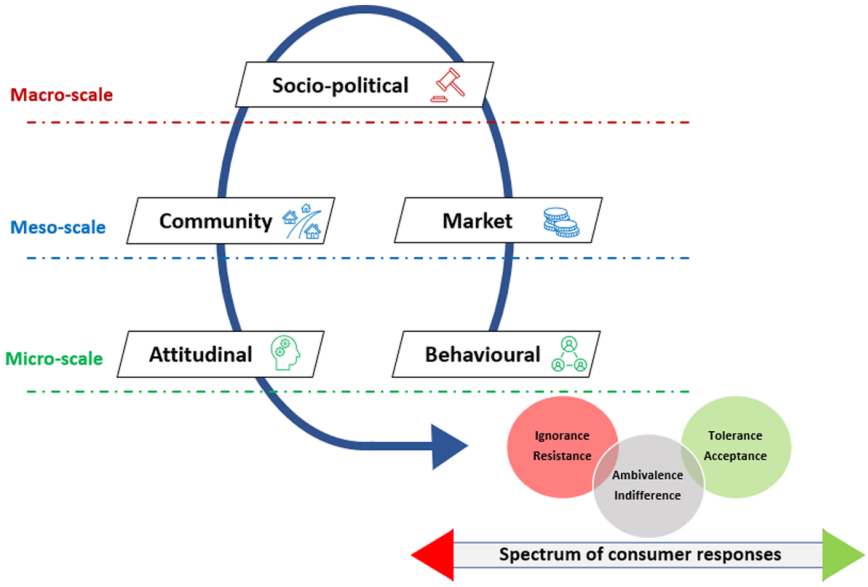

Fig. 9. The five dimensions of domestic hydrogen acceptance.

fuel poverty. At the *meso*-level, attitudinal acceptance can help consolidate community support by building trust and confidence, while also driving the potential for market acceptance by increasing consumer willingness to invest in hydrogen appliances and pay potentially higher energy bills. Finally, behavioral acceptance, if arrived to, helps realize the domestication of hydrogen heating and cooking, established on grounds on cognitive, socio-political, and socio-cultural legitimacy.

6. Conclusions

The consumer-facing side of the domestic hydrogen transition can only begin to be understood meaningfully through a critical, multi-dimensional approach to the study of social acceptance, which moves beyond the traditional dimensions of socio-political, community, and market acceptance. In drawing this conclusion, three key contributions have been made to the energy transitions literature, which can help facilitate clearer theoretical, conceptual, and empirical insights, as social acceptance research continues to evolve.

The first contribution is to provide a detailed analysis of the current state of research on the social acceptance of RETs. To the authors' knowledge, a clearly structured review of the literature is yet to be presented following the three waves of research identified by Batel [61]. Accordingly, future studies should take stock and move beyond criticism approaches by internalizing more critical perspectives. This can be achieved by examining social acceptance in multiple ways, several of which can be feasibly combined: through an energy justice lens; by accounting for spatio-temporal factors, socio-historical forces, and power relations; by applying a multi- and cross-scalar perspective; and above all, by recognizing the dynamic nature and richness of potential consumer attitudes and responses, as visualized in the social acceptance matrix. Accordingly, researchers should adopt a systematic and holistic approach that is conceptually and methodologically designed to explain the interdependency and interaction between relevant causal factors of social acceptance [111].

The second contribution is to unpack the main actors and key factors underpinning the social acceptance of domestic hydrogen in the UK context, situated according to their respective dimensions and scales. To date, information on domestic hydrogen trials and demonstration projects has not been presented in the academic literature, and moreover, these activities have not been matched coherently with corresponding evidence on hydrogen acceptance (i.e. results survey studies and focus groups). This synthesis provides a more concrete starting point for both stakeholder and spatial analysis. The research community should respond by analyzing key socio-political, socio-economic, socio-cultural, and geospatial parameters [45,292,293], supported by the application of ANT- [294,295], and SRT/SPT-based approaches [22,185].

Building from these core findings, this study presents a key conceptual contribution to the energy transitions literature, represented by the five dimensions of domestic hydrogen acceptance framework. Examining this configuration has revealed that hydrogen acceptance is more likely if the technology delivers net economic gains for the national economy, which trickle down to the population in a tangible way, for example, through employment opportunities, income security, and community development. Moreover, the emerging spatial dynamics of the UK hydrogen economy, characterized by industrial clusters and regional hubs, entail strong implications for energy justice and social acceptance. In turn, future hydrogen studies should unpack the impacts of place attachment and place identity on public perceptions, community support, and trust in key actors.

Ultimately, domestic hydrogen acceptance will rest on whether consumers view it as an economical, reliable, efficient, and fair technology, which will uphold safety standards and trust in the gas network, while living up to its net-zero promise. The transition to hydrogen homes must seek to deliver on all these fronts without exacerbating the propensity for fuel poverty or compromising the lived experience of heating or cooking. As the concept of hydrogen homes shifts towards becoming a tested and more familiar proposition for decarbonizing residential heating and cooking, scholars should internalize these findings to ensure social acceptance is considered critically: as a multi- and cross-scalar phenomenon; operating dynamically and unpredictably alongside a rich matrix of potential consumer responses. Such a commitment can direct the ongoing wave of social science research towards a more integrated understanding of how to support and accelerate a fair and efficient hydrogen transition in candidate cities and towns.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualization, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement.

Data sharing not applicable no new data generated.

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APPENDIX D. Divergent consumer preferences and visions for cooking and heating technologies in the united kingdom: make our homes clean, safe, warm, and smart!

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Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Conceptualisation, Writing – review & editing, Supervision.

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Original research article

Divergent consumer preferences and visions for cooking and heating technologies in the United Kingdom: Make our homes clean, safe, warm and smart!

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ABSTRACT

Decarbonising the global housing stock is imperative for reaching climate change targets. In the United Kingdom, hydrogen is currently being tested as a replacement fuel for natural gas, which could be used to supply low-carbon energy to parts of the country. Transitioning the residential sector towards a net-zero future will call for an inclusive understanding of consumer preferences for emerging technologies. In response, this paper explores consumer attitudes towards domestic cooking and heating technologies, and energy appliances of the future, which could include a role for hydrogen hobs and boilers in UK homes. To access qualitative evidence on this topic, we conducted ten online focus groups ($N = 58$) with members of the UK public between February and April 2022. The study finds that existing gas users wish to preserve the best features of gas cooking, such as speed, responsiveness and controllability, but also desire the potential safety and aesthetic benefits of electric systems, principally induction hobs. Meanwhile, future heating systems should ensure thermal comfort, ease of use, energy efficiency and smart performance, while providing space savings and noise reduction, alongside demonstrable green benefits. Mixed-methods multigroup analysis suggests divergence between support levels for hydrogen homes, which implies a degree of consumer heterogeneity. Foremost, we find that domestic hydrogen acceptance is positively associated with interest and engagement with renewable energy and fuel poverty pressures. We conclude that internalising the perspectives of consumers is critical to enabling constructive socio-technical imaginaries for low-carbon domestic energy futures.

1. Introduction

Following several decades of mixed scientific, technological, and commercial progress [1,2,3,4], hydrogen is increasingly recognised as an important pillar of the energy transition [5,6,7]. Given its versatility as a decarbonised gas and chemical store of energy, hydrogen offers an important energy vector for supporting global decarbonisation [8,9,10] across key sectors of the global economy [7] including industry, power, transport and buildings [11]. Hydrogen continues to attract increased attention from policy makers as a means for reducing carbon emissions [12,13,14] and strengthening national energy security [7,8,15]. This perspective is well-reflected in the British Energy Security Strategy [16][1] among other national hydrogen strategies [17,18,19,20,21]. In countries with large-scale natural gas infrastructure such as the UK, hydrogen may also present an opportunity for supporting residential decarbonisation [11,22], foremost, in proximity to the country's largest industrial clusters [23,24,25,26].

Converting the UK gas network to transport hydrogen has been

Abbreviations: CCUS, Carbon Capture, Utilisation and Storage; EPSRC, Engineering and Physical Sciences Research Council; GDNOs, Gas Distribution Network Operators; Ofgem, Office of Gas and Electricity markets; RE, Renewable energy; UKERC, UK Energy Research Centre; UK-SHEC, UK Sustainable Hydrogen Energy Consortium.

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[1] The British Energy Security Strategy recently doubled the low-carbon hydrogen production target to 10GW by 2030, adding further momentum to the emerging hydrogen economy [16].

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discussed in the literature since the early 2010s [27,28,29], following two key projects funded by the Engineering and Physical Sciences Research Council (EPSRC) [30,31].[2] Subsequently, hydrogen became increasingly discussed in UK energy policy during the mid-to-late 2010s [32,33,34].[3] Employing the UK TIMES model, Li et al. [35] concluded that low-carbon hydrogen is likely critical to greenhouse gas emissions reduction in residential heating, which has been echoed by other research findings [22,36,37]. Accordingly, some scientists posit that "hydrogen has a potentially important future role as a replacement for natural gas in the domestic sector in a zero-carbon economy for heating homes and cooking" [36:30190]. Nevertheless, the global warming potential of hydrogen [38,39] and associated environmental impacts such as methane leakage rates [40] and nitrogen oxides emissions [41,42] need to be examined further when considering future transition pathways [43,44,34,45].

Growing ambition and commitment towards realising a national hydrogen economy culminated in the release of the UK Hydrogen Strategy in August 2021 [11], following the government's Ten Point Plan for a Green Industrial Revolution [46]. The strategy aims to gather a robust evidence base by 2025 through a series of local trials and demonstration projects, ahead of strategic decision-making on the role of hydrogen for homes in 2026 [11,44].[4] Supporting the low-carbon transition, current policy plans will see gas and oil boilers banned from newbuild homes by 2025 to meet zero-carbon regulations [47], underscoring the trajectory of heating technologies in the UK.

There are around 21.2 million gas appliances and 12.7 million gas cookers (hobs and ovens) installed across the UK housing stock [48,49]. Gas is used for space heating in approximately 84 % of households [48] and remains the dominant fuel for cooking on a hob, whereas electricity is significantly more prevalent than gas when it comes to ovens [50]. While heat decarbonisation remains a significant challenge for achieving net zero [51], the emissions from cooking are embedded in the networks, institutions, and infrastructure of the wider energy system [52]. As noted by Hargreaves et al. [53], cooking practices cut across multiple regimes and system boundaries including energy, food, water and transport, thereby presenting an array of 'trigger points' for decarbonisation [52].[5]

To date, there is a clear dichotomy in the literature, as underscored by a recent output from the UK Energy Research Centre (UKERC) which examined the social side of switching from natural gas cookers and hobs to low-carbon alternatives [52]. Due to an information deficit, Khalid and Foulds [52] relied exclusively on the broader literature engaging with "heat decarbonisation, technology transition, carbon and energy reduction, home retrofitting and sustainable food consumption" to frame the study.[6] The existing knowledge gap is especially noteworthy given recent market trends, which has seen the popularity of induction hobs and corresponding sales increase within recent years [52].

Although converting to a hydrogen home, as currently envisioned, would entail a switch to new heating and cooking appliances, there is likewise scarce evidence regarding consumer perspectives of adopting hydrogen cooking appliances [54,55,56,57]. Almost exclusively, the focal point remains hydrogen heating, whereas hydrogen cooking is typically overlooked or of secondary interest. An extreme case is the UK Hydrogen Strategy which has over 400 mentions of 'heat' or 'heating' while 'cookers' or 'cooking' are referred to just five times [11]. Similarly, in their study on the public acceptability of hydrogen homes, Williams et al. [58] referred to heating approximately 16 times more than cooking. The study reported a single noteworthy finding regarding domestic heating technologies:

> …participants also disliked the idea of cooking on electric cookers, with a preference for gas cookers. In some cases, induction cookers were felt to also meet cooking needs, however, many had not necessarily experienced cooking on this type of cooker and remained sceptical [58:29].

Following these observations, this study attributes equal interest to consumer preferences for cooking and heating technologies in the UK context. Firstly, we address the research gap identified by Khalid and Foulds [52] by examining consumer preferences for existing cooking and heating technologies. Building on this contribution, the rest of the analysis aims to advance social science research on consumer attitudes towards hydrogen homes [59,60,61,62], while responding to the call for primary research on the social implications of transitioning to low-carbon cooking technologies in the developed world [52]. Critically, this study departs from previous approaches [56,59,60] by employing online focus groups as the primary method of data collection, as opposed to online or paper-based surveys. Adopting this approach, the paper makes an empirical and methodological contribution to the hydrogen futures literature [12,63,64].

The study has four distinct aims which are reflected in its structuring. Firstly, we investigate how users perceive the main advantages and disadvantages of current domestic cooking and heating technologies. Secondly, we evaluate consumer willingness to adopt hydrogen appliances and examine how this translates into wider support for living in a hydrogen home. Thirdly, we explore how attitudes towards domestic hydrogen may differ among specific consumer segments. Lastly, we assess how consumers perceive domestic cooking and heating technologies of the future. In its totality, this exploratory study can help guide future research on this topic, while offering insights to stakeholders regarding the role of consumers in the domestic hydrogen transition.

Following this introduction, Section 2 reviews the literature on consumer preferences for domestic energy technologies and hydrogen home appliances. Next, Section 3 describes the materials and methods. Section 4 reports the results on consumer attitudes towards domestic cooking and heating appliances, while Section 5 explores consumer perceptions of hydrogen homes. Section 6 synthesises this evidence base by evaluating consumer preferences for future cooking and heating technologies, which includes a multigroup analysis of domestic hydrogen acceptance. The discussion and conclusions are presented in Section 7, which maps a future research agenda and notes the limitations of the study.

2. Literature review

Given the lack of data on low-carbon cooking and consumer acceptance [52], Section 2.1 reviews consumer preferences for low-carbon heating technologies as a means for understanding wider domestic energy attitudes and behaviours, and by proxy cooking practices and preferences. Next, Section 2.2 reviews the literature on domestic hydrogen acceptance, while Section 2.3 focuses on the duality of residential decarbonisation vis-à-vis the notion of a hydrogen home. Section 2.4 documents key information regarding fuel poverty pressures and energy vulnerabilities facing UK households, reflecting our inclusion of fuel poor participants. Lastly, Section 2.5 highlights the interplay

[2] The UK Sustainable Hydrogen Energy Consortium (UK-SHEC) and the Hydrogen and Fuel Cells Supergen Hub.

[3] For example, in 2018, the Committee on Climate Change released its "Hydrogen in a low-carbon economy" report, which supported a role for hydrogen in residential decarbonisation as part of a hybrid heating system [34].

[4] Notably, Redcar in North Yorkshire and Ellesmere Port, Cheshire, have been shortlisted to host the UK's first hydrogen village trial for 2000 homes [218,219], wherein households will switch to hydrogen-fuelled appliances for heating and cooking [60,220].

[5] Cooking accounts for around 2 % of total UK carbon emissions, compared to around 14 % for domestic heating, most of which is attributed to gas boilers [52]. However, the emissions from cooking are embedded in the networks, institutions and infrastructure of the wider energy system.

[6] The deficiency of studies on consumer preferences for cooking technologies in western economies [221] also stands in stark contrast to volumes of literature tackling consumer engagement with improved cookstove programs in the developing world [222,223,224,225].

between the literature on socio-technical imaginaries and hydrogen futures.

2.1. Consumer preferences for low-carbon heating technologies

Regarding heat decarbonisation, social science research indicates how the dynamics of domestic heating practices are highly variable [65,66], with behaviours and practices shaped by a wide range of factors.[7] It has been theorised that divergent heating behaviours can be analysed by seeing where consumers fall within the following scales: spending versus comfort; single space versus differential space; regular versus irregular routines; unpredictable versus predictable routines; and self versus others [67]. Contingent on the mix of technology pathways, achieving deep decarbonisation across the residential sector may call for significant changes to consumer behaviour [32].

Reviewing the empirical literature, Kastner et al. [68] highlighted that consumers base their household energy investments around perceived consequences for energy security, thermal and operational comfort, finances and the environment. Regarding finances, Chapman et al. [69] found that 45 % UK respondents considered upfront cost to be more important than running cost, while 50 % considered the upfront costs associated with the installation of energy efficiency measures would be too expensive ($N = 5022$). Based on a comparative assessment of "the demographics and geography of household heat decarbonisation in Europe," Sovacool et al. [70:1] also found that consumers attribute more value to systems that bring economic, environmental, and cultural. Other important factors include health, safety, convenience, and comfort [70:1]. Notably, 83 % of UK respondents ($N = 2000$) valued personal control of their heating system[8] and 79 % believed low-carbon heating should be reliable and easy to use, while 56 % considered heating to be the most important domestic energy service [70]. Other studies echo these findings, with Andersen et al. [71] noting the importance of autonomy, economy and comfort in the context of district heating in Denmark, while Hagejärd et al. [72] highlight the importance of thermal comfort and control for consumer acceptance of residential space heating in Sweden.

Spatial constraints, disruptive impacts [73], noise and appearance [58] account for other important considerations when considering domestic heating appliances. For example, comparing hydrogen and heat pumps, Williams et al. [58:30] noted that "the greater use of space, lack of responsiveness, additional noise generated by the pump, and the overall look…did not tie in with perceptions of a smart home" [74,75,76]. Existing heating technology may also prove a significant determinant of subsequent technology choice [77]. Incorporating heterogenous households' preferences into the UK times model, Li et al. [35] found that 76 % of 1–3-bedroom households and 78 % of 4-bedroom households with gas heaters would opt for the same technology again.

In addition to existing technology and dwelling type (including number of rooms), age, location and awareness of eco-technology may influence homeowners' preferences for heating technologies [35]. Willis et al. [78] found that age was a significant factor in the adoption of micro-generation technologies such as solar thermal, solar photovoltaic and wind power in the UK, with consumers over 65 years old proving less willing to adopt these technologies than younger demographics. Arguably, the adoption of low-carbon energy technologies for the UK residential sector may be hindered by the country's aging population [78].

Overall, the literature suggests that low-carbon heating systems should be user-friendly and compatible with other devices, provide controllability and reliability, guarantee privacy and protect personal data, and come from credible manufacturers, preferably with performance guarantees and a customised user manual included [70].

2.2. Domestic hydrogen acceptance

Domestic hydrogen acceptance remains a nascent research area [79], with most of the evidence base originating from survey studies carried out in Australia [62,80], the UK [56,59], and Europe [81,82,83]. Gordon et al. [79] recently reviewed key findings from this literature, reporting critical concerns over cost barriers, very limited knowledge or awareness of hydrogen, and major concerns over the disruptive impacts of the hydrogen switchover [54,58,84,85]. The literature suggests the financial costs of hydrogen appliances will determine acceptance levels for most end-users [79].[9] Whether compared to other technologies [58,86] or studied in isolation [55,56,62,87], evidence suggests moderate levels of consumer support for low-carbon, domestic hydrogen.

Notably, Bögel et al. [82], and more recently, Sovacool et al. [70] conducted large sample, cross-country comparative studies. Based on a dataset of seven European countries ($N = 7148$), Bogel and colleagues [82] found that consumer support for stationary hydrogen systems for home heating and electricity was slightly more positive than general attitudes towards hydrogen fuel cell technologies. In contrast, based on a larger dataset ($N = 10{,}109$) spread close to equally across five European countries (Germany, Italy, Spain, Sweden and the UK), Sovacool and colleagues [70] found that just 11 % of respondents favoured adopting hydrogen heating in the next few years, compared to 32 % for solar, 28 % for gas and 20 % for heat pumps [70]. Thus, domestic hydrogen acceptance will depend on whether it is presented as a direct replacement for natural gas appliances or framed as one of several low-carbon technology alternatives.

Beyond these examples, most studies have relied on a single country context and in some cases comparatively small sample sizes [79]. National case studies lend themselves to exploring specific aspects of domestic hydrogen acceptance to derive context-specific findings [87], but are not always generalisable to other country contexts. Small sample studies may also prove limited in their scope to inform decision-making in a specific national context. Studies with a qualitative component have been limited to a few publications, mostly in the grey literature [54,84]. When focus groups have been employed, this method has often been selected to complement quantitative methods [58,85,86]. Principally, focus group data offers added value when implementing a sequential exploratory mixed-methods research design [88,89], wherein qualitative findings are validated by robust quantitative evidence [90].

2.3. Internalising the duality of the residential decarbonisation

Accounting for a lack of engagement with cooking technologies [52] within the discussion of low-carbon futures [79], Scott and Powells [59,60] shifted the discussion of a hydrogen home towards a more balanced level of interest in heating and cooking. Recognising the interactions between these respective sides of the domestic energy transition, Scott and Powells [59:2] advanced *a new social science research agenda for hydrogen transitions*; accounting for the ways in which hydrogen will constitute "new meanings and materialities" into daily practices of cooking and heating. Accordingly, cooking and heating practices are characterised by a complex socio-material nature [60,65],

[7] For example, behaviours and practices may be shaped by social expectations and relational dynamics, parental responsibilities, caring for pets, animals, plants (zoophilism), and underlying efforts to ensure wellbeing in terms health, harmony, comfort, or pain prevention [65,66].

[8] For example, compared to just 48 % in Sweden.

[9] Olympios et al. [226] recently modelled the cost-competitiveness of domestic electricity- and hydrogen-driven technologies from both a homeowner's and whole-energy-system perspective, reporting that hydrogen-driven absorption heat pumps [227] would be a competitive alternative to hydrogen boilers when considering total system transition costs in all hydrogen-pathway scenarios.

which reflects the richness of domestic lifestyles and homemaking practices [91].

Adopting a social practice theory approach [92,93], Scott and Powells [60:3870] further examine how "the physical and chemical properties of hydrogen may disrupt domestic practices of cooking and heating." Foremost, respondents perceived significant changes to the lived experience of cooking (i.e. hob practices) [60]. It follows that social and behavioural aspects of the domestic energy transition [94] should be understood in sync with technical and logistical challenges to support the deployment [54] and social acceptance of hydrogen home appliances [79]. This approach is especially pertinent given that most techno-economic models fail to take consumer heterogeneity into account [35], while justice and equity concerns are equally overlooked [95].

2.4. Fuel poverty pressures and energy vulnerabilities

Critically, fuel poverty pressures have been exacerbated by the COVID-19 pandemic [96] and the latest international gas crisis [97], in turn affecting consumer engagement in energy markets and energy practices [95,98]. Energy poverty levels in the UK increased nearly 50 % between October 2021 and October 2022, reaching an estimated 6.7 million households [98]. Foremost, the effects of energy poverty fall disproportionately on households with the lowest incomes and least efficient homes [98]. Regarding energy vulnerability, disabled individuals are more prone to facing fuel poverty and more likely to be on prepayment meters, which has a multiplier effect on costs, insecurity, and disconnection rates [99]. Rates of fuel poverty and disability vary according to household composition and socio-economic variables, highlighting the multi-dimensional and heterogenous nature of energy vulnerability [99]. Gillard et al. [100] further highlight how disabled people, older members of society and low-income families must contend with multiple energy injustices and vulnerabilities. In response, researchers have called for further scholarship examining "the heating phenomenology of vulnerable consumers" [65:12].

Encouragingly, the hydrogen futures literature is gradually beginning to internalise notions of equity and justice with emerging studies on the hydrogen economy value chain [101], hydrogen-based steel production [102], hydrogen imaginaries in the Netherlands [103], and green hydrogen projects in the Global South [104], including case studies on Morocco and Namibia [105]. In the residential context, consumers appear more preoccupied about the potential running costs of hydrogen appliances than purchasing costs, especially when already facing fuel poverty [56,59]. However, it is probable that ongoing cost hikes in energy bills have shaped this preoccupation, which contrasts against the findings reported in Chapman et al. [69]. Evidently, disruptive trends in energy markets further explain divergent attitudes towards respective costs factors over time.

2.5. Socio-technical imaginaries and the hydrogen futures discourse

Jasanoff and Kim [106] introduced the notion of *socio-technical imaginaries* in 2009, operationalised to a comparative examination of nuclear power in the United States and South Korea. The original definition corresponded to the attainment of desirable futures, expressed as "collectively imagined forms of social life and social order reflected in the design and fulfilment of nation-specific scientific and/or technological projects" [106:120]. More recently, Sovacool and Hess [107:719] highlighted the 'instrumental' and 'futuristic' qualities of socio-technical imaginaries, in terms of projecting "visions of what is good and worth attaining." Moreover, socio-technical imaginaries cut across multiple theories and concepts (see Fig. 5 in [108]), which has seen understanding and application of the term evolving across the social sciences literature, most prominently in Energy Research & Social Science (ERSS) Journal [108].

Interestingly, the notion of visions (or imaginaries) for a sustainable hydrogen future predates the conceptualisation put forward by Jasanoff and Kim [106], and can be traced back to at least 2006 [12], which coincided with a 'mini-hype cycle' of academic interest in the hydrogen economy [1]. Writing in 2006, Eames et al. [109] and McDowall and Eames [12] focused on the 'socio-technological dynamics' of the hydrogen transition, as envisioned by members of the United Kingdom Sustainable Hydrogen Energy Consortium (UKSHEC). Subsequently, the lead authors consolidated the theme of hydrogen futures [64,63], as reflected by Sovacool and Brossmann's [110] examination of visions and imaginaries for the hydrogen economy. As noted by Trencher and van der Heijden [111:210] "the hydrogen society agenda actively exploits rhetorical visions, narratives and imaginaries."

While socio-technical imaginaries have an explicit focus on desirable outcomes [107,111], or "the collective visions of the future and progress" [108:222], visions for low-carbon energy futures entail a more contested dimension [109]. Nonetheless, the parallel focus shared between each umbrella term (i.e. socio-technical imaginaries and visions) is apparent, and should be borne in mind when exploring low-carbon energy futures. To this point, the study of Trencher and van der Heijden [111] engages with national and local imaginaries associated with the Japanese hydrogen transition, with a focus on elements of contestation and concurrence among key renewable energy stakeholders (more aligned to the visions literature). However, to the authors' knowledge, the energy transitions literature is yet to engage concretely with visions for domestic hydrogen futures.

Socio-technical imaginaries scholarship on the residential sector has focused primarily on smart home technologies in the European context [112,113,114,115]. In most cases, insights have been gleaned from engagement with experts rather than consumers themselves, with the public typically perceived as "preoccupied with cost and visual aesthetics" [112:44]. Likewise, in the Australian context, Stengers and Nicholls [116] incorporated interviews with smart home industry professionals, offering a critique of the risks related to new energy practices and potential misperceptions of technological convenience, which the lead authors further explored when considering energy practices of the future in Australian households [117]. Against this backdrop, our study makes a novel contribution by integrating consumer visions for low-carbon cooking and heating technologies into the domestic hydrogen futures discourse, as gleaned directly from the perspectives of consumers as opposed to experts or other stakeholders (see Section 6).

3. Materials and methods

3.1. Focus groups as an instrument for qualitative analysis

Recent contributions to the hydrogen futures literature [61,118] attest to the value of the focus group approach, as a powerful tool for examining public perceptions and social acceptance of emerging energy technologies [119]. Despite limitations in terms of potential self-selection and moderator bias [120,121], as well as digital exclusion [122], focus groups provide an efficient and reliable means for gauging information on novel subject matters through collective interactions [119,123,124,125], while enabling the researcher to identify similarities and differences between participant's responses [123,126]. By facilitating freedom and flexibility, the focus group format encourages participants to arrive towards "new insights and priorities" in the process of shaping the discussion [119:280].

3.2. Recruitment process and focus group categories

Between February and April 2022, the research team conducted 10 semi-structured online focus groups with participants living in the UK

Table 1
Overview of focus groups, February–April 2022.

Focus group	Focus group category	Sample size	Recruitment method
FG1	Moderate interest in renewable energy and in joining a renewable energy community	$N = 5$	Networking with members of the local community
FG2	Strong interest in renewable energy and in joining a renewable community	$N = 6$	Networking with members of the local community
FG3	Owners of solar PV panels and multiple smart home technologies	$N = 3$	Market research company
FG4	Actively engaged in environmental issues	$N = 3$	Market research company
FG5	Living in an industrial city or town	$N = 5$	Market research company
FG6	Living in fuel poverty or facing high levels of fuel stress	$N = 3$	Market research company
FG7	Baseline group (none of the above categories)	$N = 6$	Market research company
FG8	Actively engaged in environmental issues	$N = 9$	Social media platforms
FG9	Owners of solar PV panels and multiple smart home technologies	$N = 8$	Social media platforms
FG10	Living in fuel poverty or facing high levels of fuel stress	$N = 10$	Social media platforms

Source: authors' design.

($N = 58$),[10] as shown in Table 1. The groups were purposively selected to ensure a diversity of participants, representative of specific consumer segments (see Table A1). Each category was deemed to be of primary interest to the research topic. Effectively, a socially acceptable transition to hydrogen [127], or other forms of low-carbon energy, will need to engage with potential early adopters [128,129] and demographic groups impacted by fuel poverty [130,131,132,133], as well as environmentally engaged consumers [134,135].

In each case, a Qualtrics survey was designed to match the recruitment aim. The first acceptance criteria included answering yes to the following question: *Do you currently use a gas boiler*? All participants responded *yes* to this question, while for the follow-up question concerning use of a gas hob, most participants answered *yes*. During the focus groups, a minority of respondents clarified that they had previously used gas cooking but were in the process of switching or had already switched to an electric hob. This nuance enriched the discussion around domestic cooking technologies. Other acceptance criteria are outlined in Table A1 and Supplementary Note 1.

Participants in the first two focus groups were recruited through networking with members of the local community in Marston Moretaine,[11] a village located nearby to Cranfield University, Bedfordshire. In addition to being easily accessible to the research team for networking purposes, this location was chosen in view of its engagement with renewable energy (RE), sustainability and environmental conservation [136,137]. The first group composed of participants with moderate interest in RE and in joining a RE community ($N = 5$), which served as a pilot for the study.[12] All responses and interactions recorded during the pilot matched the quality of other focus groups and the expectations of the research team, therefore, this data was deemed suitable for inclusion in the analysis. The second group from this area composed of participants with strong interest in RE and in joining a RE community ($N = 6$).

A market research company was employed to recruit participants for Focus Groups 3 through 7 ($N = 20$). Owing to a higher than anticipated drop-out rate, usually attributed to participants reporting COVID-19 symptoms, three additional focus groups were organised to fulfil the intended research design. In this case, participants were recruited through social media platforms, which proved effective for consolidating the final sample size ($N = 58$). Three specific categories were targeted during this round of focus groups (April 4–6): owners of solar PV panels and smart home technologies; individuals actively engaged with environmental issues; and citizens living in fuel poverty or facing high levels fuel stress. Based on the preliminary results, it was judged that owners of solar PV panels and smart home technologies served as a close proxy for those interested in RE and with desire to join a RE community (FG2). These sessions (FG8, FG9 and FG10) consolidated the previously underrepresented groups (FG3, FG4 and FG6). Reflecting the spatiality of the UK hydrogen transition and its link to industrial clusters, we also recruited participants from industrial cities and towns ($N = 5$). Finally, Focus Group 7 ($N = 6$) served as a 'Baseline Group' (filtering out all other focus categories) to help facilitate a potential reference point for the subsequent multigroup analysis (see Section 5.3).

3.3. Socio-structural variables

Socio-structural factors [138] include socio-demographic, socio-economic and socio-cultural characteristics [79]. Stringent filtering methods were applied throughout the survey design to ensure targeted recruitment. Quotas were set for gender and age[13] (see Table 2) to ensure a more balanced representation across the final sample. The gender quota was mostly satisfied, with a slight overrepresentation of males. However, the age quota proved harder to meet, with a significant over-representation of respondents aged 26–35, as well as under-representation of respondents older than 65. In terms of housing type and tenure, the final sample was loosely nationally representative of housing type, but less representative of housing tenure, while the average number of occupants per dwelling was somewhat higher than the UK average.

Steps were also taken throughout the recruitment process to ensure the sample covered a range of areas with location quotas set for four groups (FG5, FG6, FG7 and FG10), which accounted for approximately 40 % of the final sample. In addition to the selection of participants from Marston Moretaine, Bedfordshire ($N = 11$), approximately 34 % of the remaining sample was clustered around two locations, namely, Manchester ($N = 9$) and London ($N = 7$). Participants from Manchester and other areas of the North West of England and North Wales are situated in vicinity to the HyNet industrial cluster [139]. Together with the East Coast Cluster [23] – linking Teesside and the Humber – these respective areas were approved for Track-1 government funding in October 2021, as part of the Carbon Capture, Utilisation and Storage (CCUS) Cluster Sequencing Process [140].

The sampling strategy reflects the importance of potential synergies between the Ten Point Plan for a Green Industrial Revolution [46][14] and the UK Hydrogen Strategy [11], which focus strongly on sector coupling [32] and industrial clusters [141]. Admittedly, the final sample lacked additional representation from Wales or Scotland, and moreover, the East of England (see Supplementary Fig. 1), which should be addressed in future research.[15] Overall, while parts of the sample were relatively

[10] Participants received a cash payment of £40 or equivalent Amazon voucher as an incentive.
[11] With the Commercial Director of the Marston Vale Millennium Country Park, members of the Parish Council, and local online groups.
[12] Foremost, the research team tested the suitability of the Topic Guide, alongside the overall structure and duration of the focus group.
[13] For gender, we set an equal quota for male and female. For age, we set higher quotas for ages 25–55 to ensure our sample requirements could be met. Overall, the final recruitment process prioritised inclusion of a representative age sample, as feasible.
[14] See Point 2: driving the growth of low carbon hydrogen, and Point 8: Investing in carbon capture, usage and storage.
[15] Recruitment excluded Northern Ireland.

Table 2
Composition of sample population compared to UK population for socio-structural variables.

Socio-structural variable	Categories	Sample population (%)	UK population (%)
Gender	• Male	53.4	51.2
	• Female	46.6	48.8
Age	• 18–25	3.4	9.4
	• 26–35	36.2	13.4
	• 36–45	17.2	14.0
	• 46–55	20.7	13.7
	• 56–65	15.5	11.7
	• 65+	6.9	16.5
Housing tenure	• Owned outright	48.3	36.0
	• Owned with a mortgage or loan	41.4	27.0
	• Privately rented	6.9	19.0
	• Rented from a housing association or local authority	3.4	18.0
Housing type	• Bungalow	9.0	9.0
	• Detached house	24.0	18.0
	• Flat or apartment	21.0	21.0
	• Semi-detached house	24.0	25.0
	• Terrace house[a]	22.0	27.0
Number of occupants per dwelling	• Six	5.2	n/a
	• Five	12.1	n/a
	• Four	22.4	n/a
	• Three	20.7	n/a
	• Two	27.6	n/a
	• One	12.1	n/a
Average number of occupants per dwelling		3.1	2.4

[a] 12 % of participants lived in end-of-terrace houses and 10 % in mid-terrace houses.
Source: authors' compilation based on data from 2017 to 2020 [142,143,144].

representative of the national population, we encountered limitations in retrieving a fully representative sample, as reflected by the inherent constraints of a research design targeting a small number of focus group participants and categories [95].

3.4. Focus group format and topic guide

Each focus group ran for approximately 90 min and maintained the same structure around a set of specific topics, as described in Table 3. The same moderator led each focus group, with support from research colleagues.[16] Following a brief introduction by the moderator about the guidelines and format, participants gave their consent for recording the session. Throughout the session, participants were probed with follow-up questions to give more specific details and explanation for their views. For the most part, participants proved very forthcoming with information on each technology and required minimal prompting.

Parts 1a and 1b of the topic guide (gas cooking and gas heating) provide the qualitative data for engaging with the first research question, while Part 5 (willingness to adopt domestic hydrogen appliances and support for hydrogen homes) provides the qualitative and quantitative data for answering the second and third research questions. Drawing on the answers provided in Part 2b, insights from these strands are merged to address the final research question concerning cooking and heating technologies of the future. Taken together, the data analysed in this study represents approximately 30 % of the focus groups dataset.

Statements from Part 2a on climate change and the environment

[16] Working at Cranfield University's School of Water, Energy and Environment (SWEE).

Table 3
Overview of focus group topic guide and format.

Section	Theme	Questions and discussion topics
Part 1a	Gas cooking	• What do you like most about cooking on a gas hob? • What do you dislike about cooking on a gas hob? • What would a better cooking system look like in terms of future improvements and upgrades?
Part 1b	Gas heating	• What do you like most about having a gas boiler? • What do you dislike about your gas boiler? • What would a better heating system look like in terms of future improvements and upgrades?
Part 2a	Climate change and environmental issues	• What are your views about climate change and the environment? • How do you think the UK is doing compared to other countries in tackling climate change? • What actions do you take to help the environment?
Part 2b	Low-carbon technologies for cooking and heating	• Can you tell me more about some alternative technologies for heating and cooking? • Can anyone share some information about hydrogen? • What are your sources of information about hydrogen?
Part 3a	Formal introduction to hydrogen: Information provision round 1 (PowerPoint slides and Video 1) and poll question	Poll Question 1: • How do you feel about the government's twin-track approach, with a role for both blue and green hydrogen? (Measured on a five-point Likert scale: Very opposed–Very supportive)
Part 3b	Initial perspectives on hydrogen	• Please can you explain your answer to the poll – what are your initial feelings about hydrogen?
Part 4a	Trust levels in key actors and stakeholders of the UK hydrogen transition: Information provision round 2 (Video 2 and PowerPoint slides)	• How do you feel about trusting the main actors and stakeholders of the hydrogen transition? • How do you feel about having a choice when it comes to switching to hydrogen?
Part 4b	Community benefits, costs, and risks of the hydrogen switchover: Information provision round 3 (PowerPoint slides)	• What do you see as the potential benefits of hydrogen for your local community? • What do you see as the potential costs or risks of hydrogen for your local community?
Part 4c	The disruptive impacts of hydrogen homes and energy vulnerabilities	• How long would you be willing to be temporarily disconnected from the gas grid during the switchover? • How do you feel about engineers and technicians having access to your home during the switchover?
Part 4d	Choices and decisions regarding energy suppliers, appliance brands and models	• Has anyone changed their energy supply in the last few years or more recently? • How would you go about choosing your energy supplier if using hydrogen? • How do you feel about having a choice about appliance brand and model?
Part 4e	Cost factors around the purchasing, running and maintenance of domestic cooking and heating technologies	• How do you think the cost of hydrogen appliances should compare to natural gas appliances? • How do you think energy bills for hydrogen should compare to natural gas? • What cost impacts do you expect

(continued on next page)

Table 3 (*continued*)

Section	Theme	Questions and discussion topics
		when it comes to maintenance of your appliances?
Part 5	Willingness to adopt domestic hydrogen appliances and support for hydrogen homes	Poll Question 2: • How would you feel about switching to a hydrogen hob? (five-point Likert scale: Not willing at all–Extremely willing) • How would you feel about switching to a hydrogen boiler? (five-point Likert scale: Not willing at all–Extremely willing) • Overall, how do you feel about switching to a hydrogen home with both a hydrogen hob and boiler? (five-point Likert scale: Very opposed–Very supportive) • Please can you explain your answers to the poll?
Part 6a	Critical messages for key stakeholders	• Imagining a future where you have to choose about using hydrogen, what would you like to know most of all before making a final decision?
Part 6b	Overall support level for domestic hydrogen	Poll Question 3: • Overall, how do you feel about hydrogen homes being part of the UK's energy future? (five-point Likert scale: Very opposed–Very supportive) • Please can you explain your answers to the poll?
Part 7	Summing up and conclusion	• Do you have any final comments on tonight's topics or key reflections?

were transcribed, wherein the sample demonstrated a moderate level of awareness about these issues for the most part [145]. Notably, Part 2b provided an opportunity to verify if participants had pre-existing knowledge of hydrogen and in what context they were familiar with the technology, if at all. Across the sample, only five participants proved moderately knowledgeable about hydrogen, usually attributed to an engineering or teaching background [146]. This concluded the first part of the session, enabling the moderator to formally introduce hydrogen as the main topic of the focus group. Thereafter, findings from Parts 3, 4, 6 and 7 of the topic guide are reported in respective analyses on socio-political and market acceptance for domestic hydrogen [147], and public perceptions of the twin-track approach and domestic hydrogen futures [146].

3.5. Information provision materials

Information provision materials, consisting of PowerPoint slides and short videos, were incorporated into the session to help establish a basic knowledge level about hydrogen and its emerging applications for decarbonisation (see Table A2 and Supplementary Note 2). These materials adhered to the UK context in line with the research framing. The first video, aired by Channel 5 News on August 17, 2021 – coinciding with the release of the UK Hydrogen Strategy – presents largely pro-hydrogen perspectives from industry and government, conveying a sense of optimism and realism. Additionally, a scientific perspective from Greenpeace cautions of potential risk factors linked to hydrogen:

> The government needs to manage this whole process extremely carefully to ensure that we're not locked into high emissions that other countries aren't interested in and actually become something of a drag on UK [net-zero and energy security] ambitions (Dr. Doug Parr).

The news segment ended with details of the hydrogen blending trials taking place in the North of England, specifically at Gateshead [148,149]. However, the name of the project – HyDeploy – or any other projects in the pipeline went unmentioned [150,151].

The subsequent video was largely impersonal, featuring a brief demonstration of a hydrogen thermostat by Northern Gas Network's Hydrogen Programme Director (Tim Harwood). This video segment can be considered on the one hand as a promotional piece for hydrogen homes, but on the other hand, for newcomers to hydrogen it presents a relatively neutral (i.e. unemotional) overview of domestic hydrogen appliances, as demonstrated at the test site in Gateshead. Foremost, the video was restricted to captions exclusively, which minimised its potential emotional influence.

3.6. Data analysis

Following examples in the energy transitions literature [61,119,152,112], focus group recordings were transcribed and inductively coded on a statement-by-statement level in NVivo12 qualitative data analysis software, [153], thereby, preserving a full account of the collected data [154]. The initial coding procedure provided an effective means for exploring the textual data and processing it into distinct nodes and sub-nodes [155]. Thereafter, we screened these items for validity and reliability, while identifying areas of concurrence and divergence in the data. Following this process, the next stage involved systematically reorganising the retrieved themes through subsequent manual coding, making for a robust two-stage coding procedure [156]. Taken together, these methods reflect the iterative and non-linear process of thematic analysis [157], which provides a means for detecting and identifying factors which explain participant observations [158]. Thereafter, we conducted an interpretive qualitative content analysis [159,160], as a means for systematically organising and quantifying participant statements according to emergent themes and sub-themes [118,161].

To help transmit the focus group data, illustrative quotations are provided to capture participant observations, alongside summary tables [61,95,162], which create a sense of 'narrative weaving' within the analysis [89,118,163]. In parallel, we undertake a multigroup analysis of consumer attitudes towards hydrogen homes by evaluating descriptive statistics from poll results. Taken together, the qualitative and quantitative results contribute towards a mixed methods data analysis [164,165,166] of low-carbon domestic energy futures (see Fig. 1).

4. Consumer attitudes towards cooking and heating technologies

4.1. Perceived advantages of gas cooking

At the start of each focus group, participants were invited to discuss what they like most about using a gas hob. Around half of the sample (N = 30) provided comments regarding the perceived advantages of cooking on a gas stove. A total of seven factors were identified through the coding process, which translated to 53 items across the sample (see Supplementary Note 3). For the most part, the benefits of gas cooking were characterised in terms of controllability and ease of use (N = 19) and efficiency and responsiveness (N = 19), with 12 participants mentioning both benefits. For example, one respondent explained how "*gas is easy control…can turn it up and down and it responds to whatever I'm cooking*" (F9:1), while a professional chef remarked how "*when it comes to usability, gas is much more controllable and provides instant power*" (FG2:3). One participant reflected how "*with a gas hob, the rings cool down a bit faster and that helps avoid burning compared to electric which retains the heat*" (FG2:1), while another shared their experience as follows: "*I've used a multitude of different cookers and I like the gas hob because it's so quick and responsive, and controllable*" (FG7:5).

Among less frequently cited benefits, respondents highlighted the reliability of gas in the event of electricity cuts, its perceived familiarity, convenience advantages, and space saving benefits. In several cases,

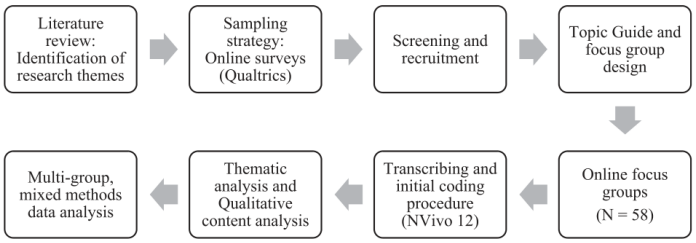

Fig. 1. Research procedure and methodology.

respondents drew comparisons to electric-based cooking appliances to highlight their arguments (see Table 4).[17] For example, one participant described the way in which a gas hob "*holds the heat and cooks quicker and better, and more even*" (FG8:6), while others mentioned how it provides "*good cooking uniformity*" (FG3:2), and "*heats thoroughly and cooks meals properly*" (FG6:2) with "*more consistency*" (FG4:1). Insightfully, a domestic caterer elaborated how the gas stove is an important staple for both their business and family life, "*…with Asian cooking it means we're making lots of chapatis which we can't make on the electric hob*" (FG10:2). In framing this detail, the participant explained how culinary knowhow had been disseminated by their elders. In turn, the low-carbon cooking transition should account for the impact of socio-cultural factors including the passing down of cooking practices between generations [65] and preferences for specific cuisines in order to safeguard against adverse distributional impacts [52].

4.2. Perceived advantages of gas heating

The perceived advantages of gas heating were discussed with a similar response rate to gas cooking ($N = 32$). A total of nine factors were identified through the coding process, which translated to 63 items across the sample (see Supplementary Note 3). Six of the seven factors associated with evaluating the perceived advantages of gas cooking (excluding *cooking consistency and uniformity*) composed the factors identified for heating; reinforcing the overlap between these two aspects of residential decarbonisation.

Mirroring the discussion on cooking, the most cited factor for heating was efficiency and responsiveness. One respondent explained how "*it's much quicker to heat with a boiler…within a few minutes you get heat through the radiators*" (FG2:3), while another commented how "*the new boilers are very efficient which helps a lot too*" (FG3:2). Compared to the discussion gas cooking, controllability and ease of use received less (direct) mentions ($N = 5$). One respondent described their combi boiler as "*very quick, reliable and easy to use…it's just there and ready to use with an easy switch*" (FG7:3). Another participant elaborated on the perceived advantages in more detail: "*If you look at central heating, it's pretty efficient in the fact that it's controllable and warms up the home pretty rapidly. The controllability and speed of response of the gas boiler is good*" (FG3:1). The observed discrepancy between statements on controllability and ease of use for each technology may be accounted for by the associated benefits of gas boilers, which include reliability, convenience, and quiet performance. In this respect, when accounting for indirect references, controllability and ease of use received more attention than efficiency and responsiveness ($N = 23$), as illustrated in Fig. 2.

In terms of reliability and convenience, one participant noted how "*Combi boilers deliver hot water all the time on-demand*" (FG7:1), while another respondent explained how "*you've always got constant heating and hot water which is what you want. It's just convenient, I guess*" (FG4:1). Relatedly, one participant described their gas boiler as both "*convenient and quiet*" (FG1:1). Additionally, regarding the discrete nature of

Table 4
Consumer perceptions regarding the perceived advantages of gas cooking and gas heating.

Perceived advantage	Illustrative quotations	
	Cooking	Heating
Controllability and ease of use	• *My mum has an electric hob which I hate because things start boiling over and it takes ages to bring down the temperature to control it* (FG7:6). • *With the electric hob, you have dials with numbers and need to know what level you want the hob on. Whereas with gas, you just rely on the flame* (FG8:7)	• *Yeah, I think you've got more control, haven't you? Whereas with electric heaters, they seem to take a lot longer to heat up* (FG6:1).
Convenience	• *The gas hob is really convenient and ready to go whenever you want* (FG3:3). • *It's quick, easy and convenient and much better than electric I would say* (FG5:2).	• *The combi boiler is great and convenient, and there's no need for a storage tanker. It's more useful for homes, quicker, more efficient, and very easy* (FG10:3).
Efficiency and responsiveness	• *I like the efficiency of a gas hob. Electric is slow to warm up food. I've switched from electric to gas because I find it much more efficient* (FG6:2). • *You get accustomed to gas, whereas with electric, if you're using a wok and need to reduce the heat, it doesn't really respond* (FG8:3).	• *I prefer gas over any other form of heating because it's quick and the rooms are heated in a matter of minutes* (FG5:2). • *Combi boilers provide hot water as soon as you turn the tap on, while not losing heat in a tank…if you're not using it or you've gone away for the weekend* (FG9:2).
Familiarity	• *I find cooking on gas much quicker and easier. It's something I've done all my life. I've never actually owned an electric hob. My mum had one and she didn't enjoy it* (FG10:3).	• *My parents had it, so when I moved out of the house and got married it was what I knew. I'm familiar and grew up with it* (FG1:2). • *Gas boilers are ubiquitous and the choice for most…if they have the option, then they use it – maybe 90 % of people* (FG8:2).
Reliability	• *With gas, you still have something to use if there's no electricity due to power cuts* (FG2:2).	• *With new technologies that haven't been tested fully, well, what is the lifespan of those new devices like heat pumps or other alternatives? They haven't been around for long enough, but gas is tried and tested* (FG5:1).
Space savings	• *It fits nicely into the kitchen and doesn't take up too much room* (FG3:3).	• *Gas is pretty discrete and hidden away* (FG3:3). • *My boiler is in the loft, so you literally never see it* (FG9:2).

Source: authors' design.

[17] For a comparative review of cooking technologies (gas and electric), see Table 2 in Khalid and Foulds [52].

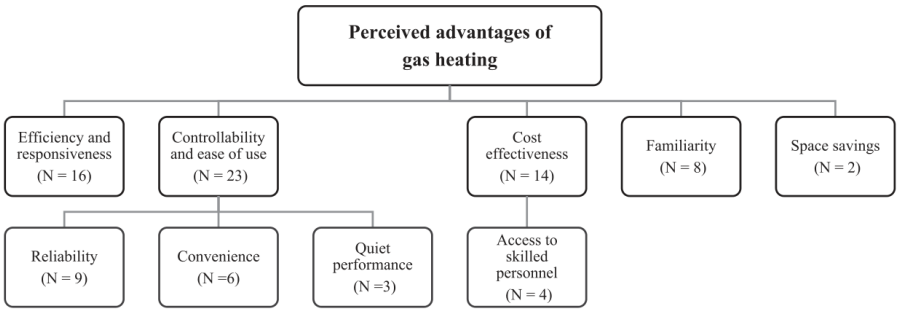

Fig. 2. Breakdown of identified themes and sub-themes regarding the perceived advantages of has heating.
Dark blue rectangles represent sub-themes of controllability and cost effectiveness, which received five and ten direct mentions, respectively.

modern boiler appliances and space saving benefits (N = 2), one participant explained how "*you can have a boiler in cupboard which you don't really hear, it sits there, and you don't notice it, which is a good thing*" (FG3:3). Taken together, the above features contribute towards higher performance and lower effort expectancy, thereby relating more broadly to ease of use. These observations mirror recent findings regarding the socio-material nature of boiler practices, which can be seen as largely 'detached', 'invisible', and 'backgrounded', compared to hob practices, which are more 'intimate', 'visible', and 'foregrounded' [60].

Notably, the performance advantages highlighted by respondents reflect the mandating of condensing boiler models for all new installations, as enforced since April 2005 through the Building Regulations amendment [167]. Relatedly, access to skilled personnel for installation and maintenance also emerged a sub-theme, which implies cost effectiveness. For example, one participant described gas as "*tried and tested…if something does go wrong with it, there's always going to be gas engineers available with experience*" (FG5:1), while another commented to the same effect, "*you have so many people out there that can easily change and maintain your gas boiler*" (FG2:5).

Aside from efficiency advantages, factors linked to cost and familiarity featured prominently in the discussion. Regarding cost effectiveness, participants noted how the "*the gas boiler is probably still the most cost-effective* [technology]" (FG5:3), while "*the combi boiler is the best solution…electric heating is currently very expensive compared to gas*" (FG10:2), with gas also being "*significantly cheaper to run if you're having mains gas*" (FG9:2). In terms of familiarity, one respondent framed the positive legacy of gas boilers in the UK:

> *I grew up with coal fires where the heat remained in one place to begin with and we also needed a paraffin heater upstairs and little electric fan heaters, so we had different kinds of heating throughout the whole house. For me, the gas boiler is ideal* (FG5:2).

Echoing these sentiments, another participant shared their experience as follows: "*Gas cooking is what I was taught, what my parents had and what I learnt to cook on, so it was just that continuation…it's much easier and what I've always used*" (FG8:7).

Overall, consumer attitudes towards gas heating reflect findings in the literature, reporting high levels of customer satisfaction due to natural gas boilers fulfilling the following key requirements: high levels of thermal comfort, responsiveness, convenience, and familiarity [168]. Indeed, thermal comfort is typically viewed as the critical factor in determining the adequacy of indoor environments [169]. Additionally, the results demonstrate the extent to which consumers value the socio-material nature of gas heating, as a discrete product and service, while also prizing access to reliable maintenance services.

4.3. Summary of findings on perceived advantages of gas cooking and heating

To conclude this part of the analysis, Table 4 presents a selection of illustrative quotations from the dataset concerning the perceived advantages of gas cooking and heating, with an emphasis on comparisons to electric alternatives, while Fig. 3 compares the number of responses between the six themes identified for both technologies.

4.4. Safety perceptions of cooking technologies

The safety aspects of domestic cooking weighed heavy on the mind of several participants, with close to one-third of the sample contributing to this part of the discussion. However, the debate was considerably one-sided, with only two respondents highlighting the perceived safety benefits of gas cooking. One participant argued in favour of gas as follows: "*From a safety point of view, you can see what you're doing. Whereas with electric, kids are at a greater risk of sticking their hands on a hob that's still hot. That's less likely with a flame*" (FG8:3). In the words of another participant, "*gas feels like cooking without any kind of hazard*" (FG5:2). One respondent also commented on the perceived safety benefits and risks of a gas flame, which drew agreement from fellow participants:

> *Physically, you can see the flame…you've got that visual representation right in front of you, whereas with electric it's pretty difficult to gauge. But the flame can also be a negative, especially when having children in the house since it's quite accessible* (FG6:2).

To the first point, respondents shared similar concerns, with one cautioning how "*…if you have kids at home, you need to be very careful about gas and kitchen activities and watch them carefully*" (FG10:7), while other participants concurred how "*the leaky flame is the biggest risk*" with young children not being able to "*realise the intensity of the heat*" (FG4:1; FG4:3). At the same time, securing the kitchen environment for children was acknowledged as mostly an issue of parental responsibility (FG4:1; FG4:3). To the second point, several participants reliant on old cooking systems and facing fuel poverty (FG6:1; FG6:2; F10:2; F10:3; F10:6; F10:7) expressed specific concerns regarding the risk of "*gas explosion incidents*" (FG10:2). In some cases, these worries were communicated in terms of fear and anxiety: "*I'm always scared because I don't want the gas to be used too much and for there to be a fire outbreak. I'm scared about the damage it could cause with gas leakage*" (FG9:3). Another participant from the same focus group reinforced such concerns:

> *…our gas hob is always trying to kill us! It has no automatic cut off, so I can be sat in the lounge and suddenly smell gas. It doesn't turn off correctly, so it just scares me a little bit. It's been in the house since we bought it* (FG9:1).

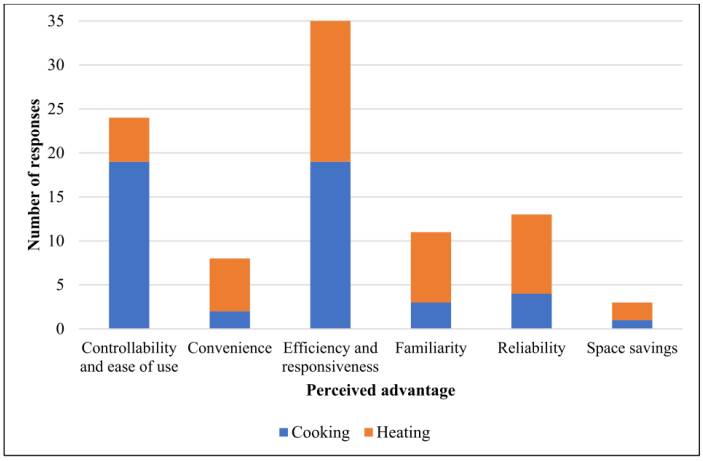

Fig. 3. Distribution of responses regarding the perceived advantages of gas cooking and gas heating.
For gas heating, only direct mentions regarding controllability and ease of use are included, while indirect references to this perceived advantage are reflected by convenience and reliability.

Issues around gas safety were further endorsed by one participant presenting a viewpoint from the fire department:

> *I prefer cooking on electric because of fire safety issues with gas. My husband is a fireman and electrician, and from a safety point of view we tend to find electric a bit safer. An induction hob tells you when it's hot* (FG1:1).

This commentary reminds how the debate around cooking safety may not always be clear-cut and can be highly context-specific, shaped by aspects such as household demographics and appliance condition. Irrespective of household composition, end-user, and appliance condition, other respondents relayed alarming episodes of setting tissues, tea towels or sleeves alight when using the gas hob (FG2:3; FG7:1; FG5:4; FG6:2). Overall, the negative safety aspects of gas cooking revolved around the risks presented by the flame itself, especially to children, and fire hazards caused by leakage. The issue of gas leakage was attributed to leaving the gas on undetected or faulty appliance condition.

In response to concerns voiced over risks and hazards, some participants countered how modern hobs offer safety features, which switch the gas off automatically when the flame is out and prevent the gas from starting up until reignited (FG2:3; FG7:4). One safety conscious participant concluded that "*more sensors are needed for monitoring gas better*," but also conceded to perceiving gas and electric "*as equally dangerous when it comes to burning your hand*" (FG10:3). While safety perceptions may hinge largely on the age and condition of cooking appliances and direct experience, one respondent shared an astute observation which can be generalised nationwide, "*I think the biggest problem is the headlines in the news when someone's house blows up, which is very rare with electric. It's usually gas*" (FG8:2). These comments reflect the ongoing prevalence of gas leakage and explosions [170], which has left some UK communities 'reeling', with safety experts demanding the government to take firmer investigative action [171].

4.5. Perceived disadvantages of gas cooking

Gas cooking was viewed largely positively for its overall performance and mostly negatively in terms of safety, albeit with mixed views which are highly context-dependent. Notwithstanding, five specific themes were identified concerning the perceived disadvantages of gas cooking (see Table 5 and Supplementary Note 3). Interestingly, a minority of respondents regarded electric cooking appliances to hold a relative performance advantage, particularly in the case of induction hobs. For example, one respondent described induction as "*an efficient technology in its own right which gives immediate control, and most of the*

Table 5
Consumer perceptions regarding the perceived disadvantages of gas cooking.

Perceived disadvantage	Total number of responses	Illustrative quotations
Cleaning and maintenance	9	• *I tend to prefer a halogen oven or pizza maker because the gas hob is too much hassle to clean, and stuff gets splattered everywhere. With the others you just take the tray out and stick it under the sink, so it saves time* (FG7:1)
Cost concerns	5	• *Gas is becoming more expensive* (FG3:3) • *Some of these new cookers can be really expensive* (FG5:4). • *The cost of gas installation can be a problem* (F8:3).
Environmental impacts	5	• *I hate using gas for what it is* (FG2:3). • *Gas cooking is not very environmentally friendly* (FG3:3). • *I would have preferred to avoid* [*a gas cooker*] *because I don't want to burning stuff basically* (FG8:2).
Efficiency drawbacks	4	• *Condensation is sometimes an issue if you haven't got much ventilation, which wouldn't happen so much using electric* (FG5:1). • *There's a lot of wasted heat with gas cooking which makes it a bit inefficient…it's okay in the winter because it warms up the kitchen nicely but it's a lot of wasted heat in the summer* (FG7:4). • *The gas hob can be a bit of a nightmare during summer because of the ventilation, which is a reason to cook more outside during the warmer months* (F8:3).
Kitchen aesthetics	2	• *Gas hobs look outdated compared to a nice, sleek halogen or ceramic hob which is aesthetically a lot nicer and less clunky* (FG7:5)

Source: authors' design.

electricity that's used to run it will convert into heat, so perhaps there's not as much wastage as with gas" (FG9:2).

Cleaning and maintenance issues emerged as the main disadvantage of gas cooking. Several participants concurred that gas hobs have a propensity to accumulate grease and is cumbersome to clean. Other respondents also drew comparisons to induction hobs which were regarded as "*something you can wipe down easily*" (FG9:2), in stark contrast to the difficulty of cleaning "*the fiddly little burners*" (FG1:3) and "*trying to get into the nooks*" (FG7:2) when dealing with gas hobs. Additionally, one participant further characterised cleaning and maintenance as posing "*the biggest problem*" because "*you have to lift up two heavy grills…so the design is a problem, especially if you are mobility impaired or disabled*" (FG7:1). Overcoming this drawback of traditional gas hobs is critical to alleviating the impact of energy vulnerabilities, which are often overlooked by technology designers and policy makers alike [172,173].

The aesthetics of cooking appliances also emerged as a minor theme of the discussion. Building on the observations around cleaning and maintenance issues, participants further agreed that gas is "*a bit old fashioned*" (FG7:4) and "*cumbersome with styles that are outdated*" (FG7:3). In response, several respondents expressed willingness or preference to move to electric-based forms of cooking such as "*an air fryer or a microwave which has combo for electric grilling*" (FG7:4) or a "*ninja pressure cooker…used for everything except baking*" (FG5:5), which "*…a lot of people are using nowadays as popular replacements*" (FG10:2). One participant went as far to say that "*…it would be better if they made electricity come on at the right temperature and then we would all probably get one* [electric hob], *wouldn't we*?" (FG5:4). This key observation reflects the significantly slower recovery rate[18] of electric cooking appliances, which is twice that of natural gas [52].

Previously, when discussing the advantages of gas cooking, only one participant had mentioned how the affordability of gas over electricity provides "*a significant benefit*" (FG9:2). When it came to highlighting the downsides, one respondent voiced frustration at having to pay £200 to install a gas oven when moving house (FG5:5). Another participant went into detail about how having "*just spent a huge amount of money on a gas cooker…nearly £1000 and over £100 to have the gas connected*" during a kitchen renovation (FG8:2). These costs were deemed unjustified and attributed to a shortage of gas engineers in the South West of England:

> *…for whatever reason where I live, gas engineers are a lot more difficult to come by than electricians…I watched him do it and it's simply push a socket in and turn it. It felt very rude and unfair paying this kind of money for someone who was in the house for about five minutes, but he had to come from a long way away* (FG8:2).

Such experiences reveal how installation and maintenance costs may vary according to both housing design and location, which may result in potentially wide disparities across the UK for consumer charges. Such trends could impact risk perceptions of switching to a new domestic technology, as part of the hydrogen switchover. To support the conditions for a socially acceptable transition, the hydrogen supply chain will need to be robust [1,174], with significant resources allocated towards training a skilled workforce for appliance installation and related logistics [175,176].

The environmental impacts of cooking with natural gas were mentioned sparingly within the wider discussion of negative factors, raised as an issue in just three focus groups (FG2, FG3, and FG8); corresponding to participants interested in RE, and owners of solar panels and multiple smart home energy technologies. The lack of responses could reflect an underlying consciousness, and in some cases explicit knowledge, among respondents that gas heating is the principal source of residential carbon emissions. While appearing a limited priority area for most respondents in this part of the discussion, environmental impacts featured more prominently in the debate around home heating (see Section 4.6).

4.6. Perceived disadvantages of gas heating

Foremost, respondents discussed the perceived disadvantages of gas heating in respect to cost factors and economic concerns. Most concerns and complaints regarding domestic heating revolved around the rise of gas prices and energy costs in the UK, with several participants bringing to life the reality of fuel poverty pressures:

> *I agree that cost is always a concern, and at the moment the price of everything is going up but utilities seem to be starker. I suppose it's something that's harder to control whenever you've got your heating on, even if you've got a smart meter. If it's cold, you have to put the heating on to have your shower or bath. I know you can cut down on these things… but I think the costs for everybody is a big concern* (FG4:1).

In this respect, and as similarly noted by Sovacool et al. [95] fuel poverty pressures have intensified since the time of data collection, which is likely to have exacerbated cost concerns and negative perceptions of the gas industry, while adding to an already pronounced trust deficit in the government and energy companies [147]. Overall, worries over cost factors relate to the purchasing price for boilers, insurance and maintenance charges, the lack of financial support or incentives for low-carbon heating, and most prominently, energy bills, including how they are calculated (see Tables 6 and A3).

Participants also commented on the size, visibility, and noise of gas boilers on a few occasions with somewhat mixed reviews. One participant concluded that "*you get used to the size of a gas boiler if that's all you've ever known*" (FG1:2), while another admitted that the boiler "*can be a bit noisy when the burners start to fire up if you've got one in your kitchen*" (FG9:2). Another respondent expressed dissatisfaction about the noise of their old boiler, which is supposedly "*very efficient*" according to gas engineers (FG6:3). Despite a strong desire to change boiler, this participant remained limited due to a lack of agency, associated with the principal-agent problem [177][19] of living in rented accommodation, which has also been documented by Sandri et al. in the Australian context [61]. Notably, all respondents in Focus Group 6 – living in old properties in the north of England and experiencing fuel poverty – shared similar complaints about the size, noise, and aesthetics of their gas boilers. Although limited to relatively few observations, issues around carbon monoxide poisoning and carbon emissions were also flagged, as reported in Table 6.

4.7. Consumer concerns over electrification

In the process of discussing the drawbacks and shortcomings of gas heating, several respondents drew comparisons to electric-based counterparts, namely, heat pumps and plug-in heaters. The next two subsections review consumer perspectives on each technology.

4.7.1. Drawbacks of heat pumps

Observations regarding heat pump technology were made spontaneously within six focus groups (FG2, FG3, FG4, FG5, FG8 and FG9). When prompted about alternative heating technologies, two other focus groups (FG1 and FG7) also commented about heat pumps. Interestingly, participants experiencing fuel poverty failed to mention any details about heat pumps (FG6 and FG10), which could be attributed to a combination of factors, such as general lack of familiarity with the technology, affordability issues, and unsuitability for installation due to poor thermal performance within the home [47].

[18] The time taken for oil to come back to temperature after uncooked food has been added [52].

[19] Whereby the desires or goals of the landlord (principal) come into conflict with those of the tenant (agent) (see [228]).

Table 6
Consumer perceptions regarding the negative perceptions of gas heating.

Perceived disadvantage	Total number of responses	Illustrative quotations
Carbon monoxide and carbon emissions	4	• *I'd much rather move away from having gas because of fumes and the environmental damage they cause. Also, the danger of explosions* (FG2:3). • *I have various Nest alarms*[a] *around the house because I'm paranoid about carbon monoxide* (FG9:1). • *You are technically burning fossil fuels and creating nothing but CO_2 at the other end, so there is an environmental impact on it* (FG9:2).
Cost concerns	8	• *The cost impacts haven't been massive yet, but come April we keep being told that it's all going up, so we're not looking forward to that* (FG1:3). • *The cost has been in the news so much lately and it's going up so much now… you've got to watch the pennies. I am concerned about it you know, so we will be looking at ways to save money on our heating* (FG4:2). • *The worry for a lot of us is the cost of these new forms of heating. It's very expensive, isn't it. The money in the discount scheme is very little compared to the cost of the new heating system* (FG5:4).
Size, noise, and aesthetics	5	• *I absolutely hate how much space my boiler takes up as a huge part of the kitchen, an entire corner! Yes, it's in a cupboard but that space could be better utilised* (FG6:2). • *Yes, same for me as well, but mine's [gas boiler] not in a cupboard. It looks quite ugly. There are pipes going up to it and it's big* (FG6:1). • *We've got a system boiler which is noisy because the water drips from the loft into the tank, and we've got pumps and a normal gas boiler downstairs…and we're about to have all that replaced and moved downstairs because of the noise of it* (FG9:1).

[a] See https://www.plumbnation.co.uk/nest/.
Source: authors' design.

Notably, a retiree lamented how they "*would never get the payback on investing in a heat pump*" (FG5:3), while another respondent of retirement age (FG3:1) drew comparisons between solar PV panels and heat pumps when considering the investment implications. However, most remarks revolved around technical barriers. For example, a solar PV owner from the South West of Scotland reflected on their experience with heat pumps:

> *We were investigating a few years ago whether to install a heat pump or to get a new gas boiler. Apart from the fact that you need to leave a heat pump on all the time, which is a negative, it also makes quite a lot of noise and depends on the type of house you have. In our case we don't have wall cavity insulation, so it wouldn't work given the size of our house* (FG3:2).

Another participant talked pragmatically from their experience in the buildings trade, "…*that's right, it's a passive thing. First, you have to fill the cavity, but older houses need better insulation to make them more efficient to reduce the demand for heating*" (FG2:5). Along these lines, one respondent described heat pump technology as having "*never quite been suitable*" for their current property (FG9:1), while another mentioned how "*heat pumps need much bigger pipework and radiators*" (FG3:1).

A systems engineer elaborated on the problem of technology lag and cost risks:

> *I do think there's this kind of lag in technology sometimes. I'm in a 1930s house which I'm slowly doing up now, but it's kind of ripping up the floorboards and insulating under it. You have to do it piecemeal sort of thing, while still living in it. But all the time technology is improving. Hopefully, I have the sort of efficiency by the end of the year where I can go for a heat pump, but until they sort of become mainstream, the price is quite high. They are now saying we've reached a point where solar panels have dropped 80 % in price, so you don't want to invest too early. You risk paying a lot more and the technology being less efficient than later systems, when the efficiency and performance of heat pumps improves. But to get those working in an old house, you first have to do a hell of a lot of work*! (FG8:4).

Participants with aspirations to join a RE community also agreed with one another that "*heat pumps are too disruptive*" (FG2:4), with one comparing them to electric vehicles in terms of infrastructure barriers and public aversion (FG2:3). Concerns about the reliability and performance of heat pumps were also contrasted against the practical advantages of boiler installation:

> *Heat pumps are noisy outside, cause lots of vibration potentially and not as efficient in the hardest, harshest of winters when it's minus 10 °C, so you're always going to need a plan B. Whereas with gas, you've already got the plumbing in place normally, so it's a quicker job to get it replaced* (FG9:2).

Reflecting some of the underlying scepticism towards the technology, one participant had "*heard that these heat pumps aren't the panacea that people say they are and they're actually quite expensive to run*" (FG7:1). This statement reflects how technologies that are yet to penetrate the market may enter the public consciousness by word of mouth, while remaining largely unfamiliar. By contrast, heat pumps have reached a high level of market penetration throughout Scandinavia, while France and Germany have become European frontrunners [178]. Researchers have found that the unfamiliarity of heat pumps [47] remains a significant barrier to adoption in the UK [58,178], which provides a critical lesson for the diffusion of other low-carbon technologies such as hydrogen.

4.7.2. Drawbacks of electric heaters

All groups mentioned the use of either plug-in electric heaters or experiences with immersion heating. Plug-in electric heaters were disliked due to their inability to heat individual rooms quickly (FG2, FG6, FG9), while three participants from the same focus group (FG7) fixated on the high costs of using immersion heater. One talked about how "*it was total nightmare for cost*" (FG7:3), while another recalled her parents command, "*thou shalt not use the immersion heater*!" (FG7:6), with the third agreeing "*it's still really expensive*" (FG7:5). Another participant relayed her recent experience of ongoing cost challenges:

> *We had an electric boiler installed last year and it had so many problems and faults that it cost a lot more money, so it was actually cheaper to run a gas boiler over several years than it was to run an electric boiler for one year*! (FG1:1).

On this theme, another participant commented that immersion heating "*takes time compared to an instantaneous gas boiler, and the cost to heat that water for an electric is much higher*" (FG8:3). Similarly, one respondent explained how "*gas gives you immediate heat and it's very controllable, unlike storage heaters which would heat in the night, and then you get immediate heat in the morning, but come evening it's all gone away*" (FG9:2). Such observations match findings in the literature, which characterise electric storage heaters as requiring a specific "process of learning through experience" for effective use and management [179].

Insightfully, one participant summarised their take on the available technology options, or lack thereof:

> *There's not a lot of choice really. You either go for gas or for electric and you have to plan ahead. I've had electric in the past with storage heaters*

and you almost have to predict what the weather is going to be in the next few days and turn it on early enough to make sure your house warms up. Going with something else is likely to be very expensive. I'm trying to go with underfloor heating at the moment, but it's a very big move to make (FG8:5).

Underfloor heating was also mentioned in the first focus group as being "*cosier*" since it "*spreads the heat out more*" (FG1:1). However, according to the same participant, most individual households are constrained in choosing this technology and reaping potential efficiency gains, irrespective of cost factors:

I do think the environmental side of things is at the design level, so if the house is designed to be more energy efficient or the building is more energy efficient, then that's fine. But if you're in an old property with gas central heating, then your kind of limited to a certain extent on how eco-friendly you can be (FG1:2).

In this respect, it is well-documented how the UK faces a domestic energy efficiency crisis [180,181,182,183], owing to a significant part of the population living in houses well over a century old [183,184], which struggle to meet energy efficiency standards [70,182]. The UK has the oldest housing stock in Europe with around 38 % of homes built before 1946, of which 21 % are pre-1919 builds [143]. As documented by Roberts et al. [183], there are approximately 8.5 million 'hard-to-treat' dwellings in Britain (~30 % of the total housing stock), responsible for around 50 % of carbon emissions from the domestic sector [185]. While low-carbon heating technologies continue to develop, implementing available energy efficiency measures – especially for aging parts of UK housing stock and in fuel poor or off-grid areas – should be front and centre of heat decarbonisation strategy [178].

Overall, consumer perceptions align closely to recent survey findings in the UK context, wherein close to 30 % of respondents believed new electric heating technology would fail to heat the home as well as gas, while 41 % considered the running costs of an electric heating system would be too expensive [69].

5. Consumer attitudes towards hydrogen homes

Taken together, the results reported in Section 4 are broadly consistent with previous findings in the literature. Notably, Chapman et al. [69] reported that ease of use, convenience, reliability, and controllability ranked as the most important attributes of gas cooking and heating, whereas electric cooking and heating (sourced from renewables) were regarded as considerably safer and significantly more environmentally friendly [69]. In addition to affirming these findings, this study addresses the limitations of most previous research on the topic (e.g. [52]) by treating cooking and heating as separate entities and undercovering areas of convergence and divergence among key acceptance factors. The next two sub-sections turn attention to the topic of domestic hydrogen acceptance by reporting results from the polls conducted towards the conclusion of each focus group, and the subsequent discussion, in which respondents explained their respective positions.

5.1. Analysis of quantitative data

Building on the comparative analysis and as a means of engaging directly with the domestic hydrogen transition, participants were asked the following poll questions to determine their attitudes towards switching to a hydrogen home:

(1) *How would you feel about switching to a hydrogen hob*?
(2) *How would you feel about switching to a hydrogen boiler*?
(3) *Overall, how do you feel about switching to a hydrogen home with both a hydrogen hob and boiler*?

The third question set out to test whether the proposition of both appliances differs substantially from responses for each technology individually. As discussed here, the results suggest a prevailing tendency of consumer support for hydrogen homes above support for either pathway individually.

The response rates for each poll question were close to 90 %. Consumer willingness to switch to hydrogen cooking and hydrogen heating proved near equivalent, as measured according to a five-point Likert scale (*Not willing at all*, *slightly willing*, *somewhat willing*, *very willing*, *extremely willing*): $M = 3.56$ for cooking, $M = 3.62$ for heating. Firstly, a notable response pattern emerged wherein *not willing at all* registered as a response for hydrogen cooking ($N = 2$), but not hydrogen heating. This distinction was explained by an expressed preference for induction hobs. Next, responses proved near equal for *slightly willing* ($N = 3$, $N = 4$) and moreover, for *somewhat willing* ($N = 19$, $N = 20$), which was the most common answer. Furthermore, responses provided identical for *very willing* ($N = 17$) and *extremely willing* ($N = 9$), showing both the discrepancy between these levels of willingness, as well as consistency among consumer perspectives towards each technology.

Interestingly, when asked about switching to a hydrogen home, as opposed to individual technologies, support levels increased significantly: $M = 4.14$ (1–5: *Very opposed*, *somewhat opposed*, *neutral*, *somewhat supportive*, *very supportive*). Most respondents were either *very* or *extremely supportive* of hydrogen homes, compared to around half being *very* or *extremely willing* to switch to a hydrogen hob or boiler. Regarding less favourable responses to the prospect of a hydrogen home, only five respondents held a neutral view, while a single respondent proved *somewhat opposed* and *very opposed*, respectively.

Fig. 4 visualises these results but uses 'willingness level' for the x-axis to enable a more direct comparison. The subsequent analysis explores distinctions between consumer attitudes towards each pathway, and their views towards the combined prospect of switching to hydrogen appliances. Critically, the qualitative discussion reveals nuance between consumer attitudes towards hydrogen cooking and heating, which may otherwise be overlooked in near homogenous poll results. Additionally, further examination helps account for observed differences which could be partially attributed to divergent scales between poll questions.

5.2. Analysis of qualitative data

Based on follow-up statements, several observations are noteworthy when distinguishing between the two pathways. Firstly, some consumers consider hydrogen cooking as a slightly more attractive option than hydrogen heating, largely owing to a perception that switching to a hydrogen hob is less risky, disruptive, or costly compared to a hydrogen boiler. Additionally, the proposition of hydrogen cookers may prove reasonably popular, or at least acceptable, for most existing gas users. At the same time, it should be noted that a lack of willingness or complete disinterest in hydrogen cooking typically stems from a preference for alternative electric-based options (i.e. induction hobs), which some respondents had already invested in or planned for. In recent years, induction hobs have taken an increased market share in the UK, following their energy efficiency and safety advantages [186]. Accordingly, patterns of technology diffusion for electric cooking [187], both in terms of speed, scale and location [188,189] will also impact the desirability and acceptability of hydrogen cooking across UK geographies and different parts of the housing stock.

When questioned about what would support moving from *somewhat willing* position to a *very* or *extremely willing* position for appliance adoption, respondents mostly cited the need for more information and better understanding about key factors such as costs and safety. For example, one respondent posed a series of questions:

…are they vastly different to gas appliances? And what about safety? Cause right now, you can smell gas and you know it's dangerous if it's left on. Is hydrogen the same, is it explosive, it is dangerous, can you smell it if it leaks somewhere? (FG1:4).

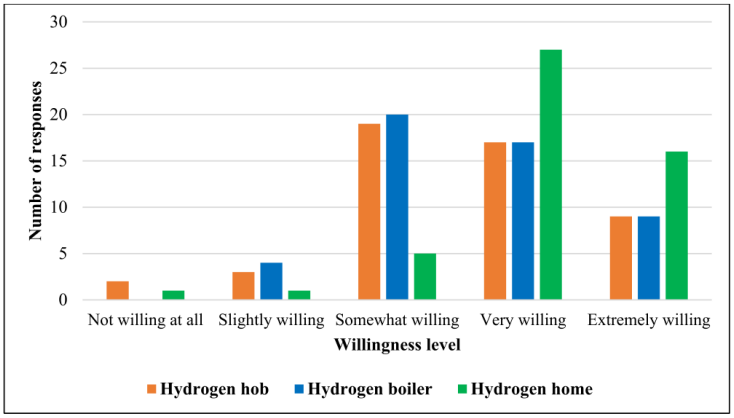

Fig. 4. Consumer willingness to switch to domestic hydrogen appliances and support for hydrogen homes.
Green bars from left to right = Very opposed, somewhat opposed, neutral, somewhat supportive, and very supportive.

Specifically, around one-fifth of participants provided direct explanations for preferring either a hydrogen hob or boiler, or both appliances, which in some cases reflected widespread agreement within groups regarding these preferences.

At the same time, it should be noted that consumer preference in this context does not infer the option of remaining on natural gas for one technology and switching to hydrogen for the other. Foreseeably, a grid conversion to hydrogen would entail a coordinated switchover for both cooking and heating appliances, although hydrogen blending may present an interim step [148,149]. This reality is mirrored in ongoing discussions over whether boiler appliances should be labelled as 'hydrogen-ready' [190] or 'hydrogen-capable' [191], and how such decisions may influence consumer perceptions and protection. This development reinforces the overshadowing of hydrogen cooking in the current discussion. The status quo lends credence to the argument that electric-based alternatives may become increasingly prevalent in UK kitchens, in line with certain consumer preferences expressed in this study.

Based on the evidence presented in Table 7, consumer preferences towards hydrogen cooking and heating were associated with specific justifications. Firstly, a common viewpoint is that a double conversion would help minimise costs and disruption, which may prove a strong selling point for hydrogen homes. Reflecting on costs and disruptive impacts, one solar PV owner framed their willingness as follows:

> *Cost and disruption are what it comes down to for me. How disruptive is it going to be to change appliances and how much is it going to cost…and if the running costs are lower, is it worth changing? It's all to do with finances and the disruption. I'm somewhat willing but need to do more research* (FG9:1).

Secondly, although a notable minority, some respondents prioritised installing a hydrogen boiler over a hydrogen hob due to the greater impacts on carbon emissions reduction. While an exploratory finding given the small sample size, such perspectives are an encouraging signal for the heat decarbonisation agenda. Technology decisions which consider emissions intensity can feasibly become more widespread, as environmental and energy technology engagement grow.

Thirdly, an important aspect of decision-making also revolves around risk perceptions. Consumers may associate greater risks with installing either a hydrogen hob or boiler appliance, according to past experience, perceptions of technology alternatives, and frequency of use. Finally, in terms of frequency of use and reliance on energy services, heating is usually prioritised over cooking. However, assumptions regarding dependency on respective sides of the domestic energy transition must be approached cautiously and evaluated on a situational basis according to socio-demographic characteristics and socio-cultural factors.

5.3. Multigroup analysis of domestic hydrogen acceptance

The main analysis has examined consumer responses across the sample, as a way of understanding preferences for domestic cooking and heating technologies, and willingness to adopt hydrogen-fuelled appliances. To derive additional insights, this sub-section draws on descriptive statistics to compare responses across sub-groups for converting to hydrogen cooking and heating (see Fig. 5), adopting a hydrogen home (see Fig. 6), and across all three measures (see Fig. 7).

Notably, strong interest in RE and in joining a RE community (FG2) aligns with support for domestic hydrogen, ranking first for both hydrogen cooking and heating (+0.68 and +0.61 points above the mean score). Consistent with these findings, this focus group category also ranks second in terms of support for adopting a hydrogen home (+0.32 points above the mean score). By comparison, moderate interest in RE and in joining a RE community (FG1) reduces acceptance levels across all three measures, with willingness to adopt hydrogen cooking and heating falling below the sample average (-0.19 and -0.42), although support for adopting a hydrogen home is marginally higher (+0.17). These results suggest that interest and engagement with renewable energy may increase domestic hydrogen acceptance.

Additionally, fuel poverty pressures may encourage support for domestic hydrogen across all aspects of the transition, with this focus group category (FG6 and FG10) ranking second across the sample for both hydrogen cooking and heating (+0.40 and +0.33) and maintaining a positive attitude towards hydrogen homes (+0.25). Similarly, living in an industrial town or city appears positively associated with domestic hydrogen acceptance, ranking first for the adoption of a hydrogen homes (+0.52), with two participants answering *very supportive* and three responding *somewhat supportive*. For this group (FG5), response patterns were consistent for hydrogen cooking and heating: two participants answering *very willing* and three responding *somewhat willing*. However, for these measures, mean acceptance levels proved comparatively lower in view of the five-point Likert scale (+0.08 and +0.01).

At the negative end of the acceptance spectrum [127], respondents actively engaged in environmental issues (FG4 and FG8) were comparatively less supportive of domestic hydrogen, falling below the mean

Table 7
Consumer attitudes towards switching to hydrogen cooking and heating.

Participant	Views on converting to a hydrogen home	Preference
FG1:2	• *Well, I think if you're doing one you might as well do everything. It all comes down to cost and sort of how easily you can change and what the impact is. But certainly, if I was going to change, I'd change everything.*	Cooking and heating
FG1:3	• *Certainly, if I was going to do it, I would want to do both and have a hydrogen home, not just a hydrogen boiler or hob. No point messing around.*	Cooking and heating
FG2:3	• *I would go for both without a shadow of a doubt. I'm always an early adopter, as long as I could afford it. If you could pay off the costs over three to five years, then it's acceptable.*	Cooking and heating
FG3:1	• *The boiler is the obvious one to hit first in terms of usage. I'd sooner go with the heating…because if anything went wrong with the cooking, there are alternatives. But currently, the main use of gas is central heating and that offers the biggest benefit.*	Heating
FG3:2	• *I think the boiler is most important. You can still have a hydrogen boiler and an induction hob, really. For me, if I'm going to go with hydrogen, especially because of climate concerns, then the boiler is my first priority. That's where I'm using most of the energy in the house; cooking is less and as I said, I wouldn't mind an induction hob. Most CO_2 emissions come from heating.*	Heating
FG3:3	• *I was slightly more willing to go with the cooking to start with because I just think if there was a problem, I could cook with an air fryer or something like that. Whereas the boiler is something I'm more reliant on. So, I might be a bit more reluctant to go all out on it, and rather experiment with the cooking side first.*	Cooking
FG5:1	• *I would go with the cooker first to trial that to see what it achieves, and then possibly moving to the boiler. So, taking a small step to see what hydrogen is actually like.*	Cooking
FG5:5	• *I would probably start with the boiler to make more of an impact because my heating costs a lot more than my cooking, but it would all come down to cost. If you could do the hob cheaper, you might do that first. It depends if there are any programs or incentives to do both at once.*	Heating
FG6:2	• *I'd rather have both than one. It wouldn't make sense to me, having two kinds of appliances running on two different types of systems. It just makes sense switching over everything at once.*	Cooking and heating
FG7:3	• *I feel that if you are having the disruption of a new boiler, then you may as well do both.*	Cooking and heating
FG8:7	• *The cost of getting both will be a lot, so it's better you go with one. The probability of boilers causing problems in homes is very limited. I will prefer to go with the boiler.*	Heating
FG10:8	• *I will need them both but will go for cooking more. I prefer cooking because I cook more often compared to using my boiler.*	Cooking

Source: authors' design.

score for all three respective measures (-0.52, -0.48, and -0.42 for hydrogen cooking, heating, and a hydrogen home). This finding is consistent with supplementary analysis of the focus group dataset, which reported lower levels of support for domestic hydrogen as part of the UK's energy future among environmentally engaged citizens (see Supplementary Note 4). Resistance among this group was partially attributed to concerns surrounding the twin-track production approach (i.e. 'blue' and 'green' hydrogen).

Somewhat of an outlier in this study were owners of solar PV panels and smart home technologies (FG3 and FG9), who fell among the mid-level for hydrogen cooking (-0.19) and hydrogen heating (+0.30) yet ranked bottom for adopting a hydrogen home (-0.75). This result may be partly explained by variation among respondents answering the final poll question and is otherwise attributed to a small sample size ($N = 9$), excluding non-responses. Notwithstanding, subsequent studies should explore the dynamics of RE engagement to validate potential divergence between consumers owning low-carbon and smart home technologies and those expressing a strong preference to join a RE community.

Finally, the Baseline Group (FG7) approximated the average level of support for adopting a hydrogen home (-0.08). This result would suggest that controlling for RE engagement, fuel poverty pressures, and living in industrial areas, may decrease domestic hydrogen acceptance. While explorative given sample size constraints, response patterns reflect potential areas of consumer heterogeneity. Additional focus group data and large sample survey studies are needed to validate these observations, alongside unpacking the implications of low-carbon technology ownership on consumer attitudes towards domestic hydrogen futures.

In light of these findings, an alternative option for exploring the aggregate data and smoothing out some of the results (e.g. in the case where respondents reject hydrogen cooking due to an expressed preference for an induction hob) is to take the average score across all three poll responses (see Table A4). Following this procedure, owners of solar PV panels and smart home technologies rank fifth, above the Baseline Group and citizens actively engaged with environmental issues. The difference between the top-ranking group (interested in renewable energy: FG2) and bottom-ranking category (environmentally engaged: FG4 and FG8) was 0.77 points.

Overall, other patterns remain mostly consistent, with the following groups scoring above the average ($M = 3.73$, $SD = 0.36$): strong interest in RE and in joining a RE community (+0.54), living in fuel poverty or facing fuel stress (+0.33), and living in an industrial city or town (+0.20). By contrast, the following groups fell below the mean score: moderate interest in RE and in joining a RE community (-0.15), owners of solar PV panels and smart home technologies (-0.21), Baseline Group (-0.23), and citizens actively engaged in environmental issues (-0.47). It can be concluded that degrees of consumer heterogeneity may be associated with domestic hydrogen acceptance, which should present a focal point in subsequent research.

5.3.1. Investigating the influence of age on domestic hydrogen acceptance

Following Table 2, which confirmed an overrepresentation of young respondents (below 35 years old) and an underrepresentation of respondents aged above 65, we investigate the relationship between age and domestic hydrogen acceptance (see Table A5). Fuel poor respondents were outright the youngest group, with most participants aged 26–35 years, whereas the industrial towns group, baseline group, and strong interest in renewable energy groups had a diversity of respondents, averaging in the 46–54 years range. Converting respective age brackets (18–25 through to 65+ into a scale of 1 to 6) resulted in a mean score of 3.50 across the sample: falling halfway between the 36–45 and 46–54 years. To calculate the mean score for domestic hydrogen acceptance, we take the average values from willingness to adopt a hydrogen hob and boiler, and support for a hydrogen home (see Fig. 7) and compare the rankings between age (youngest to oldest) and acceptance rank (most to least) as reported in Table A5.

In summary, the results for this small-sample study suggest no clear relationship between age and domestic hydrogen acceptance, following mixed results. While rankings align for the pilot group (FG1) and Baseline Group (FG7), and conform for fuel poor respondents (FG and FG10), all remaining focus group categories present disparate rankings. It is suggested that focus group membership is likely a stronger predictor of domestic hydrogen acceptance, while other socio-structural variables such as income, gender and housing characteristics (e.g. number of occupants per property) may have a stronger moderating effect on acceptance than age. Follow-up studies should seek to validate the statistical effects of respective socio-structural variables on support levels for hydrogen homes.

6. Consumer preferences for domestic energy technologies

To conclude the analysis, this section synthesises the findings to identify consumer preferences for future domestic energy technologies.

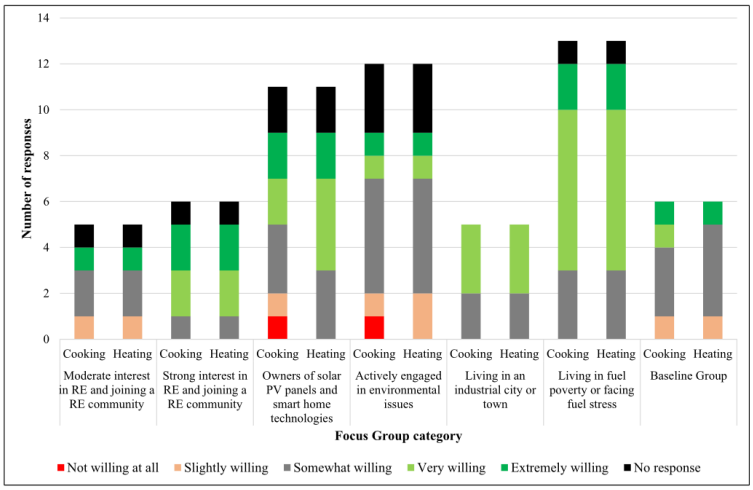

Fig. 5. Consumer attitudes towards hydrogen cooking and heating by focus group category.

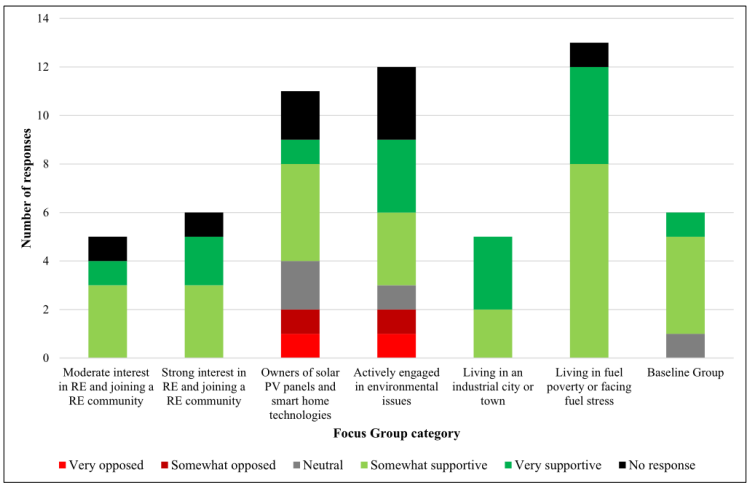

Fig. 6. Consumer attitudes towards hydrogen homes by focus group category.

Section 6.1 engages with future cooking technologies as a way of envisioning priority areas for a prospective hydrogen hob, while Section 6.2 specifies consumer preferences for domestic heating, which can be extrapolated to hydrogen boilers.[20]

[20] In this paper, we make no explicit distinction between 'hydrogen-ready' or 'hydrogen-compatible' boilers – running on natural gas but suitable for converting to run on hydrogen – which are necessary in the initial stages of deployment – and hydrogen-specific boilers. Since our study forecasts for homes of the future, or more long-term deployment, we apply the broader term 'hydrogen boilers' throughout the analysis.

6.1. Consumer preferences for future cooking technologies

Following the discussion on consumer perceptions of cooking appliances, participants were invited to describe improvements or upgrades to a domestic cooking system of the future. Reflecting the wider discussion, one respondent provided a meaningful synopsis:

Going forward, anything that is quick, safe, reliable and clean is probably going to take everything over. At the moment, you can either have electric which is slower but probably easier to keep clean, or gas with instant heat but more safety risks (FG5:2).

Other participants called for a smarter cooking system and more sensors to upgrade safety and overall cooking performance, as well as "*a more contained flame*" (FG6:2). Safety proved a critical concern for

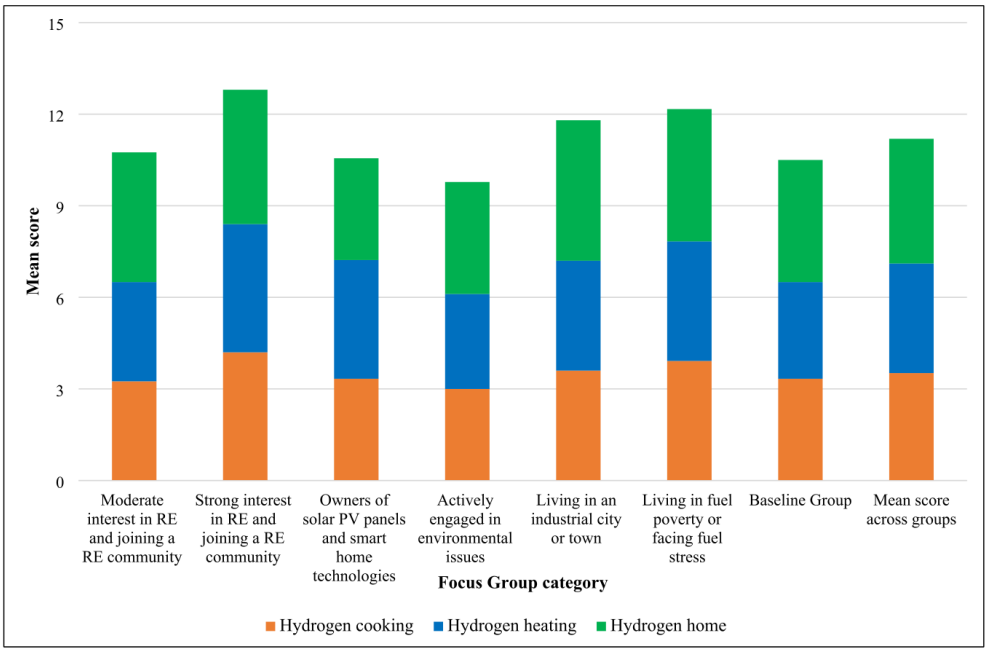

Fig. 7. Consumer attitudes towards the domestic hydrogen transition by focus group category.

consumers facing fuel poverty pressures and reliant on old cooking systems, as well as those with young family members. By contrast, one participant from the industrial towns group framed things somewhat differently:

> *…versatility of the appliance is the number one factor and ultimately the cost of running that appliance. What cost does the new technology bring for that versatility and how is that going to be balanced out*? (FG5:1).

Additionally, a minority of respondents highlighted how cooking practices can be readily handed down between generations [65], in turn shaping attitudes and preferences to current and emerging technologies. In turn, to safeguard against adverse distributional impacts [52], the low-carbon cooking transition should account for the impact of socio-cultural factors including consumer preferences for specific cooking styles and cuisines.

Synthesising the evidence base, consumers envision a future cooking hob that combines the best features of gas and electric, with a growing desire for sleeker aesthetics. When considering the prospect of hydrogen cooking appliances, it can be inferred that safety features should be prioritised alongside smart features to ensure consumers currently reliant on older gas hobs are offered a superior system. It follows that more reliable safety features are especially prized by fuel poor respondents accustomed to older and riskier gas hobs. As technically feasible, steps should also be taken to make hydrogen appliances easier to clean than their natural gas counterparts, while ensuring flame control, cooking performance and reliability are maintained, if not improved.

6.2. Consumer preferences for future heating technologies

The analysis highlights how heating preferences may be driven by multiple factors, especially cost, comfort, and convenience [192]. Furthermore, satisfaction with boiler appliances is highly influenced by the age and design of the system, reflecting the fact that UK homes are populated by a heterogenous mix of gas boilers [48],[21] which mirrors the diversity of an aging housing stock [183]. This reality underscores the potential heterogeneity of residential heat demand [193] and household energy preferences [35]:

> *One of the biggest problems in this country is that we have an elderly housing stock. The house I live in was built in 1907 and it's got solid walls, so you can't do any wall insulation and it's very difficult to insulate the property. The housing stock in this country is so old and inefficient. That's going to be a very difficult problem* (FG7:4).

Notably, one participant reinforced how low-carbon heating remains a systemic problem yet to be tackled in the UK, "*our house is only four years old and very thermally efficient, and we should have a heat pump really, so it's ridiculous we've got a gas boiler. It doesn't make any sense*" (FG2:3). Such observations underline how policy measures to ban fossil fuel boilers from newbuild homes by 2025 are arguably several years overdue.

As a way of gauging consumer desires and expectations for improvements around home heating, respondents were asked about how their domestic heating system could be improved for the future. Two respondents made explicit comments about decarbonising home heating, with one calling for "*a heating system that didn't rely on the use of fossil fuels, but instead something that was much more environmentally friendly*" (FG2:3), while the other called for more "*sustainable opportunities*" but also expressed her reluctance due to a lack of trust:

> *I'm always getting phone calls from services in the local area to upgrade my boiler…all these government grants…we've never actually taken*

[21] See Fig. 9 in [48].

anything on but would be interested to find out more. The problem is every time I get a phone call, I think it's a scam! (FG4:1).

In recent times, similar scepticism and reluctance has often overshadowed an array of "*inducements*, *instructions*, *prompts and prods*" designed by UK policy makers to motivate energy efficient home renovations [194]. Other respondents framed their comments around ensuring energy efficiency gains for heating appliances, "*so that you're not wasting energy when you use it*" (FG3:3), and "*looking at the efficiency rating to make sure the boiler's going to perform well*" (FG2:6).

Participants actively engaged in environmental issues suggested smarter monitoring "*to show you how your energy usage is affecting the environment in real-time*" (FG8:9), or using a similar device "*to cut back on energy bills*" (FG8:8). Elaborating on the environmental impact of gas heating, one self-described 'retrofit geek' stressed the difficulty of proper decision making when considering the "*green contribution*" of low-carbon technologies:

> …*what are the facts and the true carbon figures when you consider whether to go from hydrogen, heat pumps or photovoltaics*…*what are the carbon implications and environmental impacts*…*you need a balanced approach*…*to make an informed decision and I find I'm pretty much stuck, even though I work in housing* (FG8:3).

This admission highlights the need for transparency in communicating the lifecycle emissions and carbon footprint of different energy technologies for the home. However, as communicated by the following observation, technology design, resource availability, and user intentions may remain misaligned: "*We've got a new build house which has an eco-channel*…*and they have also eco-zoned our house*…*but we still use gas. It's so hard when you want to better for the environment*" (FG8:6). Such predicaments reveal the difficulty associated with consumer decision-making and when it comes to implementing measures for residential decarbonisation.

Following their grievances about their existing boilers, participants in fuel poor dwellings welcomed a "*smaller, quieter, and smarter boiler system that could be better controlled from a phone*" (FG6:2) and ideally, "*voice activated*" (FG6:3). One participant also described underfloor heating as being "…*more space saving and convenient than storage tanks and radiators*" (FG1:1), however, references to this technology were limited to just two focus groups (FG1 and FG5). Synthesising these insights, it follows future boiler systems should optimise for the following features: thermal comfort and ease of use; energy efficiency and smart performance; transparency regarding green credentials; and space savings and noise reduction.

7. Discussion and conclusions

This study addresses a research gap concerning consumer preferences for cooking and heating technologies, with a specific focus on willingness to adopt hydrogen hobs and boilers in the context of socio-technical imaginaries or visions for low-carbon homes. The analysis suggests consumers have distinct perceptions of the prospect of switching from natural gas to hydrogen appliances. Overall, the results suggest no discernible difference between consumer willingness to switch to hydrogen cooking or heating, with moderate levels of willingness and little resistance or opposition. However, when combined into the promise of a hydrogen home, consumers appear generally more supportive of this prospect and see a place for domestic hydrogen in the UK's energy future, with around one-third of respondents proving *very supportive* and close to two-thirds positioned as *somewhat supportive*. Provisionally, it appears that consumer acceptance for the transition may increase if the notion of a hydrogen home entails both cooking and heating technologies. Nevertheless, the stakes for social acceptability, as well as the environment, remain higher with hydrogen boilers.

The findings reveal that some consumer attitudes may prove more static, whereas others are likely to be more dynamic. Dynamic preferences revolve around cost, performance, fashion, and culture [195,196], thus changing with market trends, technological advancements, and culture. For example, the emergence of induction hobs marks an important transition in consumer preferences towards cleaner, sleeker and more modern cooking appliances. Similarly, technology development sees consumers expecting to upgrade to smarter cooking and heating systems when investing in new appliances. Should hydrogen hobs and boilers fail to make significant inroads in these regards, consumer acceptance may still prove feasible, provided hydrogen's environmental and safety credentials are successfully demonstrated and effectively publicised. Nevertheless, cost factors may invariably trump all other concerns for most consumers. Critically, energy costs remain subject to unprecedented unpredictability following the ongoing gas crisis [97] and Russia-Ukraine conflict [197,198,199], alongside government plans to potentially decouple natural gas and electricity prices [200].

The emergent cultural change towards stronger environmental values, embedded across parts of society and within UK households, will shape the transition. Foremost, hydrogen must prove itself as a truly low-carbon solution to compete effectively with alternative technology options such as heat pumps. Over time, the idea of intergenerational justice [201] may also play more of an active role in shaping consumer acceptability towards cooking and heating technologies. At the same time, as the domestic environment becomes increasingly populated with monitoring devices such as smoke alarms and carbon monoxide detectors, hydrogen appliances will need to reinforce a sense of security and control [202]. Safety features are especially critical to households facing fuel poverty, contending with energy vulnerabilities, or otherwise composed of young children or the elderly.

Certain consumer attitudes may instead prove rather static due to conventions deeply entrenched in culture, social norms, or behavioural needs and habits. For example, the preservation of traditional cooking for ethnic foods – reliant on gas cooking – make up a significant part of domestic life and identity for some citizens. In such instances, cooking performance linked to the flame characteristics of gas may outweigh safety or environmental concerns. On the heating side, notions of thermal comfort are entrenched in historical practices and socio-cultural norms, wherein "conditions and concepts of comfort" have been reproduced for decades, albeit with widespread differences across locations and demographics [203]. Consequently, many consumers have deeply rooted practices for thermostat management, which may also vary significantly within the same household [204].

Notwithstanding, as Shove et al. [203] argue "meanings and definitions of comfort are not set in stone." A case in point within this study are participants from Focus Groups 6 and 10, who were selected due to facing conflicts between the choice of *heating or eating* during winter months. In turn, fuel poor households must often rely on secondary solutions and measures, such as extra clothing and blankets, and hot water bottles, [205,206], among other fallback options [95]. Fuel poverty exemplifies the gulf between parts of UK society; underpinned by a heterogenous housing stock populated by a wide range of cooking and heating appliances, which are operated by consumers with varying levels of technical knowhow and environmental awareness. Accordingly, consumer heterogeneity must be internalised into policy making for residential decarbonisation.

In view of the unpredictability of energy transition processes, Davies et al. [207] argue that progress on residential decarbonisation calls for collaboration between multiple specialisations, including "building physicists, engineers, economists, epidemiologists, statisticians, behavioural scientists, complexity scientists, and policy makers," among others. By enriching our understanding of consumer preferences cooking and heating technologies – from the perspective of existing users of gas hobs and boilers – this analysis contributes to the behavioural sciences and policy making. Foremost, the findings can help set a future research agenda for exploring domestic hydrogen acceptance, wherein multi- and inter-disciplinary research teams coalesce to help safeguard public

health and safety, community well-being, and the environment [208], in line with the fuel poverty and net-zero agendas [209].

Future studies should also incorporate the use of in-person focus groups to allow for different group dynamics [210], which may result in additional richness and diversity in parts of the data gathering. This may also help counteract one of the tendencies observed in some of the groups, wherein responses from a minority of knowledgeable or extravert participants may have offset further engagement from more tentative participants. In part, this pattern may be attributed to personal comfort with communicating using an online platform (e.g. Zoom). For example, some respondents were cautious to communicate without first raising their hand and receiving acknowledgement form the moderator, despite being reminded to contribute openly. One participant also admitted that it was their first-time using Zoom, while a minority of participants experienced occasional technical difficulties.

In addition to reflecting the nature of group dynamics and individual personalities, the disparity between levels of active participation corresponds more directly to knowledge and awareness levels concerning energy and hydrogen specifically. Typically, participants with some engagement in environmental issues and knowledge of the energy transition assumed the lead during certain parts of the discussion, which is to be somewhat anticipated. Where applicable, follow-up work can take pre-emptive action during the design phase to minimise this pattern. Alongside ensuring a mix of focus group formats, which will allow for potential analysis between in-person and online approaches, other qualitative methods such interviews and deliberate workshops [55,61,211] should continue to enrich the evidence base on domestic hydrogen acceptance.

Researchers should also explore novel approaches which emphasise the use of alternate information provision materials [212], such as exposing different respondents to specific colouring or framing (i.e. positive and negative information) around aspects of the hydrogen transition [62,213]. Our analysis highlighted the role of information provision acutely at times, for example, one respondent felt reassured after seeing the video segments on hydrogen homes:

> *Normally when you think of a new technology, you think everything else is going to be new but the fact that those houses didn't look anything space age; just a normal house with a normal cooker and a heating system, that made me feel a lot more comfortable with it* (R5:2).

This study adds online focus groups to the repertoire of qualitative methods exploring domestic hydrogen acceptance; however, it is admittedly explorative and at best, partially representative of the UK population. Therefore, the results provide inferences, but should not be extrapolated beyond the boundaries of the final recruitment [214]. Moving ahead, the generalisability of results can be enhanced by undertaking large sample survey studies, including additional multigroup analyses and cross-country comparisons. In the UK context, clear opportunities for follow-up work include nationally representative and targeted survey studies, different sampling approaches in terms of socio-structural characteristics, as well as alternative recruitment from specific locations such as the East Coast Cluster or industrial towns in Scotland and Wales, in addition to rural areas of the country. This diversity can help inform different aspects of decision-making, especially around the socio-spatial dynamics of residential decarbonisation and the hydrogen transition. Finally, future studies can adopt an alternative approach to this analysis by conducting polls at the outset of the analysis (pre information provision), and then administering the polls a second time at the end of the study. Such an approach could help provide richer insights regarding changes in consumer attitudes and the role of information provision, while also providing a deeper narrative in respect to group differences.

Developing a comprehensive understanding of socio-technical imaginaries for domestic hydrogen futures is no easy task. However, we contend that tangible progress can be made by adopting a whole-systems approach. It emerges that consumer preferences for domestic cooking and heating technologies should be examined in parallel to the visions and ideas emanating from boiler manufacturers and engineers, housing developers and architects, policy makers, and other key stakeholders across the emerging hydrogen actor-network.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualization, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data underlying this study can be accessed through the Cranfield University Online Research Data (CORD) Repository at: https://doi.org/10.17862/cranfield.rd.20727982.v1; https://doi.org/10.17862/cranfield.rd.21081670.v1.

These materials will be released once the results are published (currently under embargo until 01/04/2023).

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Appendix A

Table A1
Breakdown of focus group categories and filtering details.

Focus Group category and sample size	Filtering details
Moderate interest in renewable energy and in joining a renewable energy community ($N = 5$)	• Most respondents answered 'possibly' to being part of a renewable energy community (one respondent answered 'probably') • All respondents expressed a moderate level of knowledge about renewable energy technology • No respondents owned solar PV panels
Strong interest in renewable energy and in joining a renewable energy community ($N = 6$)	• All respondents answered 'absolutely' to being part of a renewable energy community • All respondents expressed high level of knowledge about renewable energy technology • Half of the respondents owned solar PV panels or an electric vehicle
Owners of solar PV panels and smart home technologies ($N = 11$)	• All respondents owned solar PV panels (varying between less than one year and more than five years) • All respondents had at least six smart home technologies[a] • Eight respondents drove an electric or hybrid vehicle

(*continued on next page*)

Table A1 (*continued*)

Focus Group category and sample size	Filtering details
Actively engaged in environmental issues ($N = 12$)	• All respondents answered affirmatively to valuing the protection of nature and the environment, being concerned about climate change, prioritising government spending on the environment, and encouraging environmental education in schools • In some cases, respondents expressed willingness to vote for the Green Party or another environmental party
Living in industrial cities or towns ($N = 5$)	• All respondents satisfied the inclusion criteria solely based on their location, provided they were users of gas hobs and boilers • Attention was paid to socio-demographic characteristics when filtering the final selection, as a means of preserving a broadly nationally representative survey sample where feasible • This approach encouraged a potential mix of participants, while expediting the recruitment process
Citizens facing fuel poverty or high levels of fuel stress ($N = 13$)	• All respondents faced challenges around eating and heating decisions • Most respondents spent more than 10 % of their income on energy bills and lived in a property with an energy efficiency rating below Band D • Several respondents lived with children below the age of five ($N = 9$), while a few lived with people above the age of 65 ($N = 3$) • In some cases, members of the household also had mobility impairments or special needs (N = 3)
Baseline Group ($N = 6$)	• Uninterested in joining a renewable energy community • Not owning solar PV or multiple smart home technologies • Not actively engaged in environmental issues • Not facing fuel poverty or fuel stress • Living outside of an industrial area

[a] Smart lock, video doorbells, smart thermostat, smart alarms, smart camera, smart speakers, smart bulbs, smart plugs, smart kitchen appliances, smart light switches, robot hoovers, smart blinds, smart smoke detectors, smart TVs, garage door openers, universal robots.
Source: authors' design.

Table A2
Overview of information provisional materials.

Information type	Purpose and framing	Description of content
Animated PowerPoint slides	Factual information for newcomers to hydrogen	• Overview of the UK Hydrogen Strategy [11], explaining its links to decarbonisation around the country's largest industrial clusters [215]. • Overview of 2030 and 2035 timelines and energy demand projections for deploying hydrogen across the industry, power, buildings (for heat), and transport sectors [11]. • Overview of 'grey', 'blue', and 'green' hydrogen [216], including a map of blue and green hydrogen projects taken from the Hydrogen Strategy: "Proposed UK electrolytic and CCUS-enabled hydrogen production projects" [11].
Two-minute Channel 5 News segment on the UK Hydrogen Strategy (https://www.youtube.com/watch?v=g-VpyglBhrI)	Media representation of hydrogen giving a sense of different perspectives	• Statement from the Head of hydrogen projects, Northern Gas Networks, Tim Harwood, providing an industry perspective. • Statement from former UK Business and Energy Secretary, Kwasi Kwarteng, providing a government perspective. • Statement for Greenpeace Chief Scientist, Dr. Doug Parr, providing a non-governmental organistation (NGO) perspective.
One-minute video on the H21 Project led by Northern Gas Networks (https://www.youtube.com/watch?v=CtAzCv5Sc48) [55,217]	Bridge the knowledge gap around the use of hydrogen in homes through visual demonstration and written information	• In the UK, 83 % of homes use gas for heating and cooking. • This accounts for around 30 % of our emissions. • The H21 project, led by Northern Gas Networks is demonstrating how our gas network could be converted to carry hydrogen. • This includes trialling hydrogen boilers at three demonstration houses. • The boilers have been developed by Worcester Bosch and Baxi. • They heat homes just like the boilers we use today. • But because they burn hydrogen, they emit no carbon. And could be the least disruptive route to a net-zero carbon future.
Animated PowerPoint slide	Mapping the key actors and stakeholders of the UK hydrogen landscape	• Explaining the supply side related to different energy companies and market competition. • Explaining the role of Gas Distribution Network Operators (GDNOs) in managing the gas grid. • Explaining the role of central government and independent entities such as Ofgem (Office of Gas and Electricity markets). • Explaining the role of trades bodies and boiler manufacturers. • Explaining the role of business, industry, and academia.
Animated PowerPoint slide	Illustrating the spatial dynamics of the UK domestic hydrogen transition	• Outlining the sites of hydrogen trials and demonstration projects. • Outlining the first cities and towns where domestic hydrogen is forecasted. • Underlining the role of and location of hydrogen hubs and industrial clusters.

Source: authors' design.

Table A3
Consumer concerns regarding the costs of over gas heating.

Participant	Illustrative quotations
FG1:2	• *I pay extra insurance to get my boiler serviced every year and in case anything ever goes wrong…so I have that added security, but it does cost quite a bit. The costs are the main problem looking ahead.*
FG3:3	• *The only real downside I see is the cost keeps going up with the energy crisis.*
FG7:4	• *One of the problems with gas is it seems less precise in its measure of energy compared to electricity…with my energy company if I use electricity between 5.30 am and 12.00 am it's a quarter of the price, but no one seems to offer different rates with gas.*
FG8:2	• *Gas has cost me a fortune! I've paid about £4500 to have my boiler replaced in 2012 and about 18 months ago I spent another £800 to get it to work again. That didn't fix the problems such as broken controls or timers. It's set at a certain temperature now whether I like it or not.*
FG8:9	• *I agree that it is quite costly to repair or replace a gas boiler.*

Table A4
Mean score and rank for domestic hydrogen acceptance by focus group category.

Focus Group category	Mean score	Rank	Difference from mean score across focus group categories
Moderate interest in RE and joining a RE community	3.58	4	−0.15
Strong interest in RE and joining a RE community	4.27	1	0.54
Owners of solar PV panels and smart home technologies	3.52	5	−0.21
Actively engaged in environmental issues	3.26	7	−0.47
Living in an industrial city or town	3.93	3	0.20
Living in fuel poverty or facing fuel stress	4.06	2	0.33
Baseline Group	3.50	6	−0.23
Mean score across focus group categories	3.73		
(Standard deviation)	(0.36)		

Table A5
Analysis of relationship between age and domestic hydrogen acceptance by rankings.

Focus Group category	Mean age bracket	Mean score for age[a]	Mean score for hydrogen homes	Age rank (youngest to oldest)	Acceptance rank (highest to lowest)
Moderate interest in RE and joining a RE community (FG1)	36–45	3.60	3.58	4	4
Strong interest in RE and joining a RE community (FG2)	46–54	4.00	4.27	5	1
Owners of solar PV panels and smart home technologies (FG3 and FG9)	26–35	2.80	3.52	2	5
Actively engaged in environmental issues (FG4 and FG8)	36–45	3.30	3.26	3	7
Living in an industrial city or town (FG5)	46–54	4.40	3.93	7	3
Living in fuel poverty or facing fuel stress (FG6 and FG10)	26–35	2.20	4.06	1	2
Baseline Group (none of the previous categories, FG7)	46–54	4.30	3.50	6	6
Mean	36–45	3.51	4.08		
(Standard deviation)		(0.81)	(0.41)		

[a] Point system for calculating mean score for age: 1 = 18-25; 2 = 26-35; 3 = 36-45; 4 = 46-54; 5 = 55-65; 6 = 65+.
Source: authors' calculations.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103204.

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APPENDIX E. Gauging public perceptions of blue and green hydrogen futures: is the twin-track approach compatible with hydrogen acceptance?

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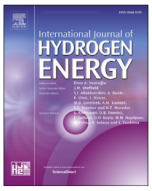

Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance?

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HIGHLIGHTS

- The UK public appears receptive to the launch of a national hydrogen strategy.
- Negative perceptions of the twin-track production approach stem from misconceptions.
- Blue hydrogen requires explanation and justification to preempt social resistance.
- Consumer buy-in hinges on access to reliable and transparent sources of information.
- Hedonic and cost concerns typically outweigh climate change considerations.

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Low-carbon homes

ABSTRACT

National hydrogen strategies are emerging as a critical pillar of climate change policy. For homes connected to the gas grid, hydrogen may offer an alternative decarbonisation pathway to electrification. Hydrogen production pathways in countries such as the UK will involve both the gas network and the electricity grid, with related policy choices and investment decisions impacting the potential configuration of consumer acceptance for hydrogen homes. Despite the risk of public resistance, be it on environmental, economic, or social grounds, few studies have explored the emerging contours of domestic hydrogen acceptance. To date, there is scarce evidence on public perceptions of national hydrogen policy and the extent to which attitudes may be rooted in prior knowledge and awareness, or open to change following information provision and engagement. In response, this study evaluates consumer preferences for a low-carbon energy future, wherein parts of the UK housing stock may adopt low-carbon hydrogen boilers and hobs. Drawing on data from online focus groups, we examine consumer perceptions of the government's twin-track approach, which envisions important roles for both 'blue' and 'green' hydrogen to meet net zero ambitions. Through a mixed-methods, multigroup analysis, the underlying motivation is to explore whether the twin-track approach appears compatible with hydrogen acceptance. Moving forward, hydrogen policy should ensure greater transparency concerning the benefits, costs, and risks of the transition, with clearer communication about the justification for supporting respective hydrogen production pathways.
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Nomenclature

CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CHP	Combined heat and power
EU	European Union
GDNO	Gas Distribution Network Operator
HETs	Hydrogen energy technologies
HFCVs	Hydrogen fuel cell vehicles
HFSs	Hydrogen fuelling stations
MMR	Mixed methods research
RESs	Renewable energy sources
RETS	Renewable energy technologies
UK	United Kingdom

Introduction

The notion of a global 'hydrogen economy' [1,2] and associated idea of a 'hydrogen city' [3] can be traced back to the 1970s and 1980s, with these concepts taking root in academic research, mainstream literature, and the political arena during the early 2000s [4,5]. During this time, scholars have debated and scrutinised the potential role of hydrogen in the global energy transition [6–10].[1] As climate change-related pressures continue to mount, [11–13], the discourse has increasingly shifted towards developing a 'sustainable hydrogen economy' [4,14,15], as reflected by a recent wave of national policy strategies and targets [16,17].

Hydrogen's attractiveness to policymakers and the energy industry stems from its unique attributes, as a potential driver of energy security [18,19], international competitiveness [19], large-scale emissions reduction [18–21], and improved air quality [18,19,21], especially via industrial decarbonisation [22,23]. Critically, hydrogen may help manage the intermittency of renewable energy sources (RESs) [24] by providing a means to store excess electrical energy [25–27]. Hydrogen is especially coveted in countries with extreme import dependency such as South Korea [28]. Moreover, the most recent gas crisis [29], coupled to ongoing market volatility and political instability linked to the Russia-Ukraine conflict [30–33] has intensified a new 'dash for hydrogen gas' in Europe to counteract energy security risks [34,35].

Notably, the European Union (EU) has growing ambitions to scale up hydrogen capacity [36–38], with European Commission Vice President, Frans Timmermans, declaring plans to position Europe at the forefront of the 'hydrogen revolution' [39]. Specifically, the EU aims to develop a hydrogen backbone, composed of dedicated pipelines spanning thousands of kilometres and cutting across multiple Member States [40–42]. Similarly, the United Kingdom (UK) is seeking opportunities for cross-border hydrogen trade with Europe [40,43]. Foremost, National Grid's Project Union entails a 2000 km hydrogen network linking major UK industrial clusters which could help facilitate this ambition [44].

Visions for a national hydrogen economy rest strongly on the role of industrial clusters in the energy transition [45,46], envisioning a transformation towards industrial 'SuperPlaces' [47] and 'hydrogen clusters' [48].[2] Industrial transformation, as exemplified through the scaling up interconnected hydrogen backbones and clusters, may prove decisive to shaping the geopolitics and international governance [17] of future markets for hydrogen energy systems [49]. In countries historically reliant on natural gas such as the UK [50,51], hydrogen may also provide a means for decarbonising the residential sector via low-carbon appliances for heating and cooking [52–54]. Released in August 2021, the UK Hydrogen Strategy [55] details how 'hydrogen homes' may form part of a hybrid strategy for residential decarbonisation, alongside heat pumps, district heating and other low-carbon technologies. Notably, the strategy supports plans to scale-up hydrogen trials in targeted localities [56,57]. To better contextualise activities around the emerging hydrogen economy, Table A1 summarises recent developments in UK hydrogen policy (see Appendix A).

Alongside policy commitments and market mechanisms [58], realising prospects for a full-scale hydrogen economy [59–61] and hopes for hydrogen homes [62] will rest on understanding and responding to public perceptions [63–65]. As Dumbrell et al. [66] explain, "the transition involves difficult choices that must be technically feasible, relatively safe, economically rational, and accepted by the public." Consumer buy-in and broader social acceptance [21,67] are prerequisites for enabling technology adoption [68], and developing a 'just hydrogen economy' [69] in support of a socially equitable energy transition [23,70]. Similarly, Ren et al. [71] highlight the importance of integrating socio-political acceptability, alongside technological, economic, and environmental criteria, when evaluating the sustainability performance and suitability of hydrogen production technologies.

While the techno-economic feasibility of decarbonising the UK gas grid via hydrogen has been explored in different energy models for over a decade [72–75], social science research on domestic hydrogen acceptance [64,76,77] has only emerged within the last few years [78]. To date, most social science research has centred on data collected from online surveys [76,79–81], whereas qualitative research grounded in deliberative methods and participatory techniques remains scarce [52,62,82]. Mixed methods research (MMR) featuring a strong qualitative element is needed to meaningfully engage the public with hydrogen energy technologies (HETs) in an active way [19,82], while broadening social perspectives on prospective hydrogen futures and applications [83]. In response, this study draws on qualitative and quantitative data collected through 10 online focus groups, which intersected

[1] For example, Sovacool et al. [5] cautioned that the hydrogen economy may reinforce a pervasive 'energy culture', in which public and individual expectations coalesce around a fantasy future "where energy is abundant, cheap, and pollution-free." The Energy Cultures Framework [255] recognises that "distinctive clusters of knowledge, belief, behaviour and material objects (as held by individuals and groups) will have some bearing on the way energy is used, along with the more decentred influences."

[2] For example, among recent announcements, the 'Green Blue' action plan aims to decarbonize London's Thames Estuary via the development of a hydrogen ecosystem on land and water [278,279].

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with key geo-economic and geo-political events affecting global energy markets and UK society [29,33].

The paper examines public perceptions of the UK domestic hydrogen transition and prospective production pathways. The aim of the research is to determine, (1) what is the existing level of hydrogen knowledge and awareness among UK consumers and what are their preferences for information dissemination; (2) what perceptions do consumers hold towards the UK government's 'twin-track' approach entailing blue and green hydrogen production pathways; and (3), how do consumers perceive the prospect of domestic hydrogen as part of the country's low-carbon energy future. While the first research question gauges attitudinal acceptance by evaluating individual and group levels of hydrogen knowledge and awareness [63,78], the remaining research questions engage with socio-political acceptance [84] by exploring consumer attitudes towards the hydrogen transition at the macro-level [63,78].

The stated aims contribute towards the main motivation of this exploratory study, which is to help steer future research and decision-making on the domestic hydrogen transition towards a socially acceptable pathway. The rest of the paper proceeds as follows. The next section contextualises the study by reviewing the hydrogen policy and acceptance literatures. The methods section describes the research design, distinguishing between the qualitative and quantitative components of the online focus group approach. Next, the results section presents the findings of the mixed-methods analysis, which are validated through a series of statistical tests to derive meta-inferences from both MMR strands. The penultimate section discusses the implications of the findings, while the final section concludes the study.

Literature review

This section reviews the literature on hydrogen production pathways and related energy policy alongside scholarly contributions which have placed 'hydrogen acceptance on the radar'. In doing so, we provide an overview of key developments in the hydrogen futures literature, as well as a more specific focus on findings related to knowledge and awareness of hydrogen, and consumer perspectives on hydrogen production technologies.

Hydrogen policy and production pathways

Reviewing the 'hydrogen futures' literature in the mid-2000s, McDowall and Eames [19] linked the drive towards a hydrogen economy with the emergence of stronger environmental values and greater support for social equity; reflected by the advent of energy decentralisation and the democratisation of RESs [85–88]. Notwithstanding, there are a range of 'technological architectures' (i.e. centralised, decentralised, and hybrid) underpinning the configuration of hydrogen production pathways in different countries and regions [83,89–91]. Technological architectures and associated policies may support a 'blue' hydrogen pathway [92], based on steam methane reformation (SMR) with carbon capture and storage (CCS); or alternatively, align with developing a 'green hydrogen economy' [93] based on production via electrolysis using renewable electricity [24,94,95]. Other production pathways – combining and balancing different hydrogen sources – are rapidly emerging as national hydrogen economies continue to evolve [8,23,96–98].

Currently, the status of blue and green hydrogen as competing or complimentary production sources varies across the globe [99,100]. For example, the Australian Government retains a technology-neutral or agnostic stance [66]. Meanwhile, Canada is exploring several hydrogen production pathways according to available feedstocks, energy inputs, and the feasibility of carbon capture, utilisation and storage (CCUS) across different regions and provinces [101,102]. By contrast, EU policy is more aligned to a green pathway [38], with ambitious commitments towards increasing electrolyser capacity in Spain [103], Germany [104], and France [105], among other Member States [106].

In the German context, evidence suggests that blue hydrogen is critical to enabling the transition to a green hydrogen economy, which rests on first decarbonising the power sector [107]. The same holds true in the UK context, wherein the equivalent of 300 GW of offshore wind power would be needed to meet forecasted hydrogen demand across the energy sector [108].[3] In response, the UK government is investing in both CCUS-enabled production and electrolysis, through its twin-track approach. In April 2022, the British Energy Security Strategy doubled the 2030 hydrogen production target to 10 GW, specifying that at least 50% should be sourced from electrolytic ('green') projects (see Appendix A). In February 2023, the government announced a consultation process for the Low Carbon Hydrogen Certification Scheme to help establish the sustainability criteria of hydrogen production, in view of strengthening market confidence and investment opportunities [109].

Policy support is needed to enable a role for blue hydrogen as a 'bridging technology' to help scale up green hydrogen methods [55,110]. However, the societal costs of pursuing this pathway must be understood and communicated [94] before new energy systems become path dependent [66] and 'locked-in' [111]. Critics of blue hydrogen suggest that social acceptance is likely to be an issue [112], given that its overall carbon and environmental credentials are less favourable than renewable-based hydrogen production [94,113]. It has been argued that the blue pathway may subvert the energy transition agenda [72,111], especially if problems, risks, and uncertainties around methane leakage rates [114,115], global warming potential [115,116], nitrogen oxides emissions [117,118] and other environmental impacts [119],[4] cannot be overcome or adequately understood. Relatedly, Cheng and Lee [120] developed a four-fold typology to evaluate the green commitments of national hydrogen strategies, finding that most countries aim to scale up production first before prioritising climate targets (i.e. 'scale first and clean later').

[3] Compared to an existing capacity of approximately 14 GW and a 2030 target of 50 GW.

[4] For example, particulate matter formation, terrestrial acidification, mineral resource depletion and freshwater ecotoxicity [119].

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Ultimately, from a climate change perspective, hydrogen is "only as compelling as its feedstock supply" [121] and the management of system processes across the value chain [122]. Critically, Velazquez Abad and Dodds [123] undertook a global review of the green hydrogen policy developments, highlighting ways in which green hydrogen schemes must develop to meet stringent sustainability criteria.[5] More broadly, research on the hydrogen economy should adopt a whole-systems approach to better account for the sustainability impacts of HETs in terms of product life cycle and waste issues [19].

Hydrogen acceptance on the radar

Hydrogen acceptance presents a burgeoning research area, supported by a relatively rich literature spanning two decades [124–126]. Mapping developments in the hydrogen economy since the early 1970s, Yap and McLellan [127] acknowledge that HETs face similar challenges to more familiar RETs such as wind and solar [128] when it comes to establishing 'global acceptance'. Critically, the social aspects of the hydrogen transition should be examined to bridge the existing knowledge gap regarding consumer preferences for HETs [127]; serving as a mechanism to help support a sustainable hydrogen economy with end-user acceptance [129]. Responding to prior reviews on hydrogen acceptance [82,130,131], Agnoletti et al. [129] affirm this point by recommending a more 'human-driven' approach to increase the desirability of HETs. Similarly, Vallejos-Romero et al. [132] identify hydrogen acceptance and consumer willingness as critical factors for responding adequately to emerging market demands, with a primary view towards the green hydrogen value chain. This study follows in this tradition by advocating for the importance of understanding consumer attitudes when designing, augmenting, and diffusing HETs.

Overview of hydrogen futures literature

To date, hydrogen technology studies have focused mainly on transport applications [133–136], principally hydrogen fuel cell vehicles (HFCVs) [21,67,137–139], hydrogen buses [140,141], and related infrastructure such as hydrogen fuelling stations (HFSs) [142]. Mirroring this focus, early studies on public perceptions of HETs concentrated mostly on the transport sector [143–146], with this research stream consolidated by recent studies in South Korea [147–149], China [150,151], India [152–154], Japan, and Australia [155]. For example, in the Indian context, Kar et al. [154] reported a positive relationship between perceived environmental benefits such as carbon footprint reduction and intention to use HFCVs, while Harichandan and Kar [152] also found environmental consciousness to positively influence consumer acceptance for HFCVs. By the same token, higher levels of environmental concern may increase the adoption intention for HFCVs [152,156].

Literature reviews conducted by Emodi et al. [61] and Scovell [64] attest to the same trends, but also highlight the emergence of studies on domestic applications including hydrogen boilers and hobs, and stationary residential hydrogen fuel cells. For example, in their comparative European study (N = 7148) Bögel et al. [157] reported lower levels of acceptance for hydrogen fuel cell technologies compared to stationary hydrogen systems for home heating and electricity. Hydrogen studies in the German context have also shifted the focus towards understanding the dynamics between local and general acceptance [146,158,159]. Schönauer and Glanz [158] investigated the acceptance of local hydrogen pipeline infrastructure and general acceptance, finding lower levels of support for infrastructure implementation in one's own neighbourhood compared to hydrogen at large. Emmerich et al. [146] adopted a similar conceptual approach, operationalised through a structural equation model (SEM), which revealed higher levels of general acceptance for HFSs compared to community-level acceptance [84]. More specifically, environmental self-identity had a positive indirect effect on general acceptance, but a negative direct effect on local acceptance, which may be attributed to the disruptive impacts of HFSs on the local environment [146].

Compared to survey studies with a predominantly statistical focus [157,160,161], which include the aforementioned studies, qualitative research on domestic hydrogen acceptance is mostly limited to studies in the grey literature [162,163] or mixed methods analyses [80,164], which are more likely to be quantitatively driven [165,166]. One notable exception in the academic literature is the study of Sandri et al. [77], which involved a stakeholder workshop with energy experts and drew on a focus group style methodology (i.e. 'breakout sessions') to gauge views on the impact of domestic hydrogen on energy vulnerabilities in Australia. Relatedly, following an inductive analysis of stakeholder views – composed of publicly-available industry submissions to the National Hydrogen Strategy and community submissions in Victoria – Beasy et al. [167] flagged the importance of community acceptance in supporting Australia's hydrogen transition. Other important contributions to the social science discussion on domestic hydrogen include the research agenda proposed by Scott and Powells [52,76], which is rooted in a social practice theory approach [168]. Through this lens, cooking and heating practices entail complex socio-material characteristics, [52,169], which account for divergent residential lifestyles and practices [170,171].

Knowledge and awareness of hydrogen

Knowledge and awareness may prove critical to domestic hydrogen acceptance, especially in the early stages of the transition [78]. As argued by Sherry-Brennan et al. [172], pre-existing knowledge creates 'reference points'[6] to which consumers 'anchor' their perspectives of HETs. Within the hydrogen futures literature, it is well-documented how a lack of familiarity with the technology constrains end-user acceptance [132,173]. As summarised in Table 1, hydrogen

[5] The recent literature has tended to focus mostly on green hydrogen policy such as the need for standards and guarantee of origin schemes [123], and other policy support mechanisms such as subsidies for enabling grid-based green hydrogen production [94,280].

[6] The notion of 'reference points' can be traced to earlier work conducted by Ricci et al. [281].

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Table 1 – Recent empirical evidence on levels of hydrogen knowledge and awareness across society, 2017–2023.

Study	Country context and sample size	Key findings
[31]	Norway (N = 1906)	• Males scored 0.66 points higher on the hydrogen acceptance scale than females (Scale 1–7).
[164]	Australia (N = 2785)	• 65% of male respondents were either 'very supportive' or 'supportive' of domestic hydrogen compared to 40% for female respondents.
[161]	Europe[a] (N = 7148)	• Mean score for awareness of different hydrogen energy technologies (hydrogen fuel cells, residential fuel-cell micro-CHP, and hydrogen fuel cell electric vehicles) across seven European countries = 42.1/100. • Mean score for the UK = 38.7, with a score of 23.0 for residential fuel-cell micro-CHP (M = 25.3 across sample).
[66]	Australia (N = 1824)	• Mean score for knowledge of hydrogen industry (additive index composing of five measures including 'How hydrogen is produced') = 3.22 (Scale 0–10); SD = 2.63.
[160]	Australia (N = 2785)	• Mean score for objective hydrogen knowledge = 2.28 (Scale 1–5). • Mean score for subjective hydrogen knowledge score = 1.49 (Scale 1–3).
[179]	United Kingdom (N = 340)	• 23.8%, 40.9%, 28.5%, 4.4% and 1.5% of respondents had not heard about hydrogen before, heard of hydrogen but knew nothing about it, knew a little, knew a fair amount, and knew a great deal, respectively.
[180]	Turkey (N = 964) (N = 415)	• 11%, 45.4% and 35.3% of respondents had not heard about hydrogen, heard about it but had no knowledge, and had little knowledge, respectively. • 81.9% of respondents had little knowledge of hydrogen while 18.1% had some knowledge.

Source: Authors' compilation.
[a] Belgium, France, Germany, Norway, Slovenia, Spain, United Kingdom.

awareness and knowledge has proven low across a range of national contexts. The underlying consensus across empirical studies is that higher educated males are typically the most knowledgeable demographic group, which correlates positively to hydrogen acceptance [126,174,175]. Conversely, consumer scepticism towards HETs has been associated with a lack of knowledge, awareness, and direct experience [82,176]. Both early [124,131,177], and more recent studies [157,160,173,178] report higher levels of hydrogen knowledge and acceptance for males.

An additional observation based on datasets from Europe [124,126,181], and Australia [164,182] is that subjective knowledge of hydrogen has increased over time, which implies positive prospects for social acceptance [78]. Furthermore, statistical results from an Australian nationally representative survey suggest a positive influence of information provision on hydrogen acceptance, equating to a 9% and 11% increase for domestic and export applications, respectively [183].[7] In the South Korean context, Lee et al. [147] also highlight the relative importance of diffusing hydrogen education to support socio-political acceptance for hydrogen buses.

Consumer perspectives on hydrogen production pathways

Regarding production pathways, the literature indicates stronger approval for hydrogen produced from RESs [31,160,179]. For example, a focus groups study conducted with the Welsh public in 2008 revealed stronger approval for carbon neutral hydrogen production methods, with wind farms perceived as a preferable energy source over fossil fuel feedstocks [175]. In the intervening years, studies in the UK [179,184] and international context [160,185] have consistently highlighted public concerns regarding the use of fossil fuels for hydrogen production [159], with overwhelming evidence in favour of renewable-based methods (see Table 2).

Bentsen et al. [31] found that Norwegian citizens held strong approval for green hydrogen (3.90) compared to blue hydrogen (3.20) and grey hydrogen (2.30), as measured on a five-point acceptance scale. The study showed climate change concern to be positively associated with acceptance for green hydrogen [31]. Another Norwegian study provided nuanced insights as to the acceptability of coupling onshore wind with hydrogen production, wherein approval for wind farms (and indirectly support for the green hydrogen sector) increased when priority was given to local decarbonisation efforts (e.g. for municipal transport and industry sectors) [189]. Examining consumer attitudes across five European countries (N = 10,109) which included the UK, Sovacool and colleagues [190] reported lower acceptance rates for hydrogen heating compared to renewable-based alternative such as heat pumps and solar. In the French context, Damette et al. [181] found that consumers were more supportive of hydrogen being converted into electricity off-site and then supplied to households using existing electricity transmission networks (i.e. power-to-gas-to-power), as opposed to gas-based alternatives. Such findings reflect the reality that the policy space around green gas and electrification pathways is often highly contested [184], if not controversial [191]. Notwithstanding, scarce studies have investigated consumer attitudes regarding attributes of different production methods in a specific national context with a publicised strategy [64]. This study seeks to address this knowledge gap in relation to the twin-track approach (blue and green hydrogen pathways), underlying the UK Hydrogen Strategy.

[7] The information package included a short video, followed by images and text descriptions. Hydrogen acceptance also proved context-dependent, with socio-economic characteristics and geographic location having a significant influence [183].

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Table 2 – Studies on public perceptions of hydrogen production methods, 2009–2023.

Study	Country context	Methods and sample size	Key findings and comparisons
[186]	United Kingdom	7 in-person focus groups (N = 47)	• Participants opposed the use of non-renewable primary sources to generation hydrogen (foremost nuclear power and coal). • Participants wanted to see more government support for renewable energy-based hydrogen production.
[185]	Germany	Computer-assisted Telephone interview (CATI) survey (N = 1011)	• 66% of respondents expressed a preference for hydrogen produced in an environmentally friendly way (i.e. not via grey hydrogen), even if this increased consumer prices. • 27% of respondents believed hydrogen should be produced from natural gas for a transition period. • 7% had no preference for either option.
[187]	South Korea	Online survey (N = 1000)	• 40% of respondents supported hydrogen produced from nuclear power. • 40% were neutral and 20% were in opposition.
[163]	Australia	9 focus groups (N = 72)	• 74% of survey respondents supported renewable-based hydrogen production. • 54% supported blue hydrogen as a transitional fuel.
[184]	England	Online survey (N = 578)	• Survey respondents preferred green hydrogen (M = 82/100) over blue hydrogen (M = 59/100) as alternatives to natural gas.
[188]	United Kingdom South Wales	Online survey (N = 464) 2 online focus groups (N = 13)	• Participants in both the survey and focus groups reported positive views of green hydrogen (produced via electrolysis), perceiving it as different from the compared technology, namely, fracking.
[179]	United Kingdom	Online survey (N = 340) 5 online focus groups (N = 25)	• 84% of focus groups respondents preferred green hydrogen production over blue or grey options. • Blue hydrogen was perceived as a somewhat acceptable transitional fuel to green hydrogen, while grey hydrogen was perceived negatively.
[160]	Australia	Online survey (N = 2785)	• A mean score of 3.63 (SD = 0.82) for the statement: Hydrogen should be produced using renewable energy and electrolysis only. • A mean score of 3.18 (SD = 0.91) for the statement: Hydrogen should be produced using fossil fuels with CCS as an intermediate step while transitioning to renewables (Scale: 1–5).

Source: Authors' compilation.

Methodology

This section describes the methods of the study, organised according to details of the online focus group approach, recruitment and sampling strategy, topic guide, and data processing techniques composing the mixed methods analysis.

Online focus group approach

Focus groups provide a powerful research tool for supporting the collection of in-depth qualitative data about emerging societal issues [192,193], such as consumer perspectives of low-carbon energy technologies [194–197]. As described by Caporale et al. [198], the focus group approach reveals insights about "participant opinions considering life experiences, expectations, and knowledge about the specific matter to debate." Notably, online focus groups have become a more common research method, especially following COVID-19 [179,199]. The online format offers distinct advantages over in-person focus groups by helping to safeguard against external events,[8] improving overall logistics, and helping to ensure diversity between or within participant groups as per the research requirements [199,200]. However, one notable caveat is that online focus groups exclude demographic groups lacking the necessary means or desire to participate in a digital environment [201]. To carry out this study, 10 semi-structured focus groups were conducted on Zoom between February and April 2022. Each focus group ran for the same duration (~90 min), retained a consistent format, and was led by the same moderator, supported by a co-moderator from Cranfield University's School of Water, Energy and Environment. This approach helped ensure consistency in terms of data collection procedures, information framing, and overall delivery and flow.

Recruitment, sampling strategy and focus group topic guide

Participants were purposively selected through different screening surveys,[9] which filtered respondents into seven distinct categories (see Table 3 and Appendix B).[10] The categories were selected given their relevance to the potential configuration of consumer acceptance for hydrogen homes, whereby a socially acceptable transition [63] will be influenced through a combination of factors: the actions and incentives of early adopters [202,203,203]; engagement from citizens living in industrial areas where the hydrogen switchover is set

[8] For example, two of our focus groups coincided with an extreme weather event in the UK (Storm Eunice).

[9] Qualtrics was used to set-up the screening surveys and to collect the data.

[10] Participants received an incentive in the form of either a cash payment or Amazon voucher.

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Table 3 – Details of focus groups, February–April 2022.

Focus Group no., sample size and date[a]	Focus Group category	Location(s) of participants	Recruitment method
FG1 N = 5 February 14, 2022	Moderate interest in renewable energy and joining a renewable energy community (Pilot)	Marston Moretaine, Bedfordshire	Networking with members of the local community
FG2 N = 6 February 17, 2022	Strong interest in renewable energy and joining a renewable community	Marston Moretaine, Bedfordshire	Networking with members of the local community
FG3 N = 3 February 21, 2022	Owners of solar PV panels and multiple smart home technologies[b]	Kilmarnock Portsmouth Torquay	Market research company
FG4 N = 3 February 23, 2022	Actively engaged in environmental issues	Ipswich Leeds Pembrokeshire	Market research company
FG5 N = 5 February 25, 2022	Living in an industrial city or town	Falkirk Flint Liverpool Scunthorpe Yorkshire	Market research company
FG6 N = 3 February 28, 2022	Living in fuel poverty or facing high levels of fuel stress	Cheshire Manchester	Market research company
FG7 N = 6 March 02, 2022	Baseline group (none of the above categories)	Deeside Eastbourne, Hertfordshire Reading	Market research company
FG8 N = 9 April 04, 2022	Actively engaged in environmental issues	Gloucester Kent Stirling Sussex	Social media platforms
FG9 N = 8 April 05, 2022	Owners of solar PV panels and multiple smart home technologies	Lancashire, Lincolnshire London Manchester North Wales	Social media platforms
FG10 N = 10 April 06, 2022	Living in fuel poverty or facing high levels of fuel stress	Isle of Wight Leeds Liverpool London Manchester	Social media platforms

Source: Authors' design.
[a] Due to low participation in some of the initial focus groups (FG3, FG4 and FG6), the research team opted to organize three additional focus groups to secure larger sample sizes for the affected categories.
[b] Smart lock, video doorbells, smart thermostat, smart alarms, smart camera, smart speakers, smart bulbs, smart plugs, smart kitchen appliances, smart light switches, robot hoovers, smart blinds, smart smoke detectors, smart TVs, garage door openers, universal robots.

to commence [204–206]; public attitudes towards hydrogen as a net-zero fuel [207,208]; and impacts on fuel poverty and fuel stress [209–211]. As a control measure, a 'Baseline Group' (FG7) was included in the analysis, which filtered out the specifications of other focus groups, thereby providing an additional measure for comparative analysis.

Supporting the research design, we applied quotas in Qualtrics (i.e. for age, gender, and location) to help target a nationally representative sample where feasible (see Appendix B). Critically, the sample included a near equal balance of male and female respondents (N = 31, N = 27). Residents from Marston Moretaine (nearby to Cranfield University) were recruited for the pilot focus group (FG1), wherein participants had a moderate level of interest in renewable energy and in joining a renewable energy community. Thereafter, participants in the second group (FG2) expressed a stronger interest regarding renewable energy, and were also regular visitors to the Marston Vale Forest Centre, which engages in climate protection [212,213] and is partly powered by a wind turbine [214]. Results from FG1 met all requirements for subsequent data analysis, which supported the suitability of the focus group format and content.

Following prior literature review on the subject matter [63,78], the research team developed a topic guide to stimulate discussion across a range of areas connected to the hydrogen transition (see Table 4). Additionally, participants received two basic types of information provision (i.e. PowerPoint slides and videos) to enable a more meaningful discussion on hydrogen (see Fig. 1). Enhancing the data collection protocol,

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Table 4 – Focus Group format.

Topic Guide category	Topic description
Introduction	
C1	• Cooking technologies and consumer preferences
C2	• Heating technologies and consumer preferences
C3	• Climate change, the environment, and renewable/low-carbon energy technologies
C4	• Knowledge and awareness of hydrogen (general) and preferences for reliable sources of information
RQ1	
Information provision round 1	
RQ2	• **Poll 1 and discussion:** Consumer views on the UK's twin-track Hydrogen Strategy
Information provision round 2	
C5	• Trust in key actors and stakeholders of the hydrogen transition
	• *Information provision round 3*
C6	• Community benefits, costs, and risks of hydrogen
C6	• Individual impacts and disruption related to the domestic hydrogen switchover
C7	• Choice of energy suppliers, appliance brands, and models for domestic heating and cooking
C8	• Costs of hydrogen appliances (purchase, running, and maintenance)
	• **Poll 2 and discussion:** Willingness to switch to hydrogen appliances and to live in a hydrogen home
RQ2	• **Poll 3 and discussion:** Consumer preferences for hydrogen in the UK's energy future
C9	• Key messages for actors and stakeholders shaping the hydrogen transition
	• Conclusion
Description of information provision	
Round 1	• PowerPoint slides on hydrogen production and the UK's 'twin-track' hydrogen strategy
	• Video on the UK Hydrogen Strategy https://www.youtube.com/watch?v=g-VpyglBhrI&t=32s
Round 2	• Video on the H21 Project https://www.youtube.com/watch?v=CtAzCv5Sc48
	• PowerPoint slide on the key actor-networks composing the UK domestic hydrogen landscape
Round 3	• PowerPoint slide on the spatial dynamics of the UK domestic hydrogen transition
Description of polls	
Poll 1: RQ1	• Consumer views on the UK's hydrogen strategy and the twin-track approach
Poll 2	• Willingness to switch to hydrogen appliances and to live in a hydrogen home
Poll 3: RQ2	• Consumer preferences for domestic hydrogen in the UK's energy future

each focus group was supported by three poll questions. In line with the specified research questions, this study reports the results from Poll 1 and Poll 3.

Mixed methods data analysis

Mixed methods research (MMR) provides a robust means for grappling with the multi-dimensionality and complexity of social issues, while enhancing the discoverability of patterns in retrieved data [216], as compared to studying qualitative and quantitative outputs in isolation [217,218]. While traditional MMR designs include a separate qualitative and quantitative phase [218,219], mixed methods data analysis can also be presented within a single method [220]. For example, Vogl [216] integrated qualitative and quantitative results from a focus groups study, and derived findings from the interactions between these two strands (i.e. meta-inferences). Thus, 'mixed analyses' can be considered as a specific variant of MMR, wherein a single round of data collection is analysed through qualitative and quantitative strands [216]. Integration brings the respective data strands into conversation with one another [218], serving to enhance the richness and explanatory power of conclusions [221].

As a focus groups study, this analysis follows a separative approach whereby the qualitative and quantitative data analyses are carried out independently of one another, before meta-inferences are drawn through interpreting and reporting the implications of the integrated findings through narrative weaving [222]. This study is qualitatively driven for all research questions (i.e. qualitative: participant statements → quantitative: poll results), which adheres to the temporal relation of the data collection [219]: polls were employed following discussion between focus group participants, as a way of further quantifying and validating their perspectives on hydrogen.

For the qualitative strand, this study applied a combination of thematic and content analysis [223], which is consistent with the approach of Smith et al. [179] in their study hydrogen perceptions in the UK context. Adhering to established protocols [77,196,224,225], the audio recordings were transcribed and inductively coded verbatim in NVivo12 [226], thus, preserving the entirety of the recorded data [227]. Thematic analysis [228] was undertaken to detect and identify patterns in consumer responses, and areas of convergence and divergence in opinions [229].

Reflecting the mixed-methods nature of this study [230,231] (see Fig. 2), the analysis includes a series of summary tables and figures, alongside illustrative quotations which capture the voice of participants and the narratives put forward [77,219,232]. Subsequently, content analysis provides a means for systematically organising and quantifying participant statements according to each theme (code) and sub-theme (sub-code) [233]. For the quantitative strand derived from poll data, statistical analyses were conducted in SPSS 27.0 to examine differences across the sample and between groups. Finally, data integration at the level of reporting key findings relies on narrative weaving [179,221], as a means for structuring the discussion and deriving meta-inferences [234].

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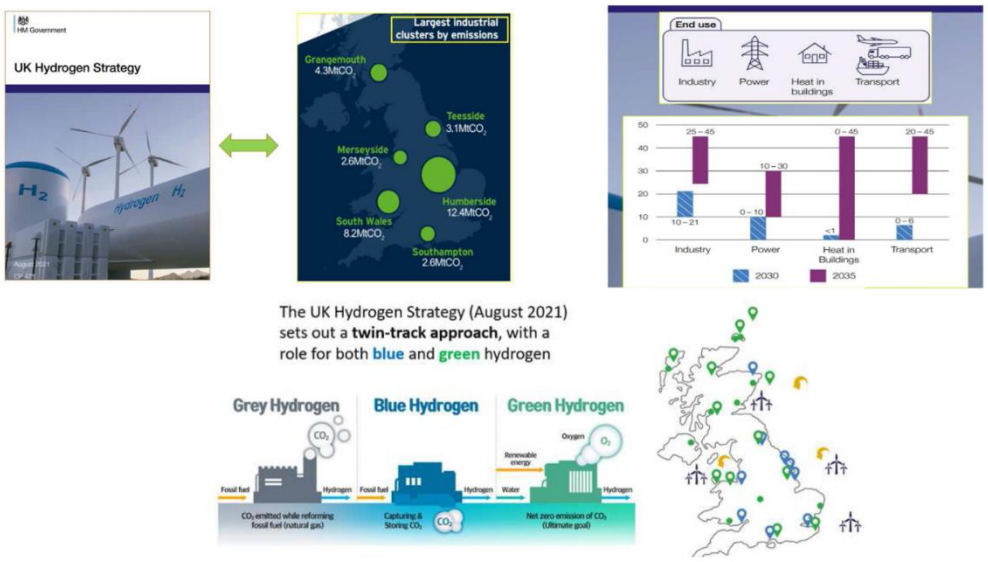

Fig. 1 – PowerPoint materials. Panel A highlights links between UK industrial strategy and the Hydrogen Strategy. Panel B shows demand projections (TWh) for UK hydrogen. Panel C contextualises hydrogen production and outlines the twin-track approach. Source: Author's design based on [46,55,215].

Results

This section reports results on hydrogen knowledge and awareness (see Section Measuring hydrogen knowledge and awareness), consumer perceptions of the twin-track production approach (see Section Consumer perceptions of the twin-track approach), and perceptions of domestic hydrogen futures (see Section Public perceptions of hydrogen futures). The section closes by unpacking consumer preferences for information dissemination on hydrogen home appliances and the domestic hydrogen switchover.

Measuring hydrogen knowledge and awareness

Prior to the moderator announcing the main purpose of the focus group, some details about hydrogen were raised spontaneously in several focus groups, with 26 individual responses recorded across the sample. Once formally introduced as the main topic of interest, participants were asked directly whether they had heard of hydrogen before and in what context, and to what degree. Accordingly, results on this aspect were provided through direct observation and validated during the subsequent analysis of transcripts. Reflecting on the findings, hydrogen knowledge and awareness was measured according to four distinct categories (see Table 5).

Participants with moderate to high knowledge and awareness of hydrogen

Across the sample, only five participants (FG2:2, FG3:1, FG8:2, FG8:3, FG9:2) proved knowledgeable about hydrogen and were informed about its potential use in homes. All participants in this category were males, aged between early-30s to mid-70s. This finding is consistent with the literature, which reports a prevalence of greater hydrogen knowledge levels among educated males [126,160,161]. Additionally, the respondents in this group had teaching or engineering backgrounds. Foremost, the technical risks and constraints of hydrogen were flagged, with a focus on safety and production concerns.

Regarding the risks of hydrogen, one participant responded "*… it can be dangerous, but then again so is gas and electricity … it's about handling it correctly*" (FG2:2). On the topic of electrolytic hydrogen, he expected "*things to go in that direction*," but worried about production costs and risks of electricity sources not being green (FG2:2). Another participant described the need to scale up domestic renewable energy capacity to support clean hydrogen production and cited storage and transportation as "*obvious problems*," while also acknowledging "*safety concerns due to the very nature of hydrogen*" (FG3:1). Reflecting on the broader discussion between hydrogen and electrification, one respondent believed commitment to either pathway presented a risk of "*being locked into that technology for maybe 10, 20, or 30 years*," which he considered an unacceptable risk (FG8:2). Demonstrating the relevance of location, a participant from Teesside explained how some of the chemical manufacturers in the area are "*looking to develop hydrogen facilities to pipe it into the mains*" (FG8:3), in conjunction with the South Bank project [235].

Finally, a participant with solar panels and smart home technologies (FG9:2) believed "*it would be much better if they*

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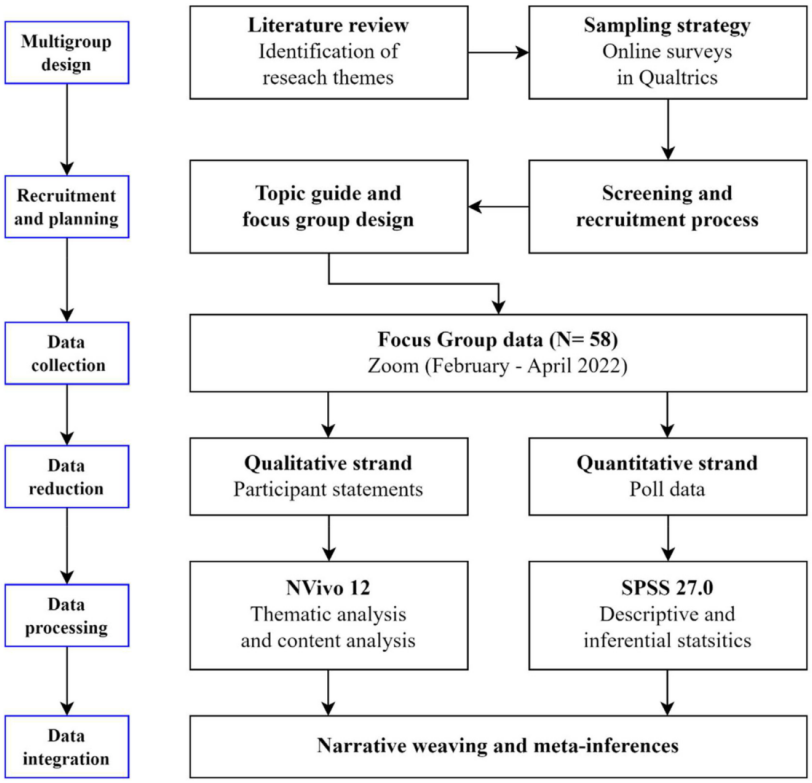

Fig. 2 – Sequential overview of research design and methods.

Table 5 – Definition and distribution of hydrogen knowledge and awareness levels in this study.

	Definition of knowledge and awareness category	Number of responses (%)
Low	• No real knowledge of hydrogen and only familiar with it by name alone	32 (55.2)
Limited	• Some knowledge and awareness of hydrogen which remains limited to basic understanding or familiarity	11 (19.0)
Some	• Ability to contextualise some examples of hydrogen applications and demonstrate basic knowledge	10 (17.2)
Moderate to high	• Familiar with hydrogen to at least a moderate level with ability to demonstrate more than basic understanding	5 (8.6)

could pipe hydrogen into houses instead of natural gas, like in Orkney" [236]. In addition to mentioning concerns about hydrogen storage, its pressure and volatility, the same respondent explained that "*… you'd need 5 kW of electricity to bubble off 1 kW of useable hydrogen, so it's absolutely fine if the grid overflows … then you could in theory dump that energy into creating hydrogen.*" While acknowledging that a lot of the infrastructure may be in place for hydrogen, he concluded that "*it's never going to be a cost-effective solution until we get ten times more renewable electricity generation*" (FG9:2).

Participants with some knowledge and awareness of hydrogen Ten participants, spread across half of the focus groups (FG1:4, FG1:5, FG2:3. FG2:5, FG3:2, FG5:1, FG5:3, FG9:1, FG9:3, FG9:8), demonstrated some relevant knowledge of hydrogen and were able to mention a few specific applications (see Appendix C). In this case, the distribution was evenly split between male and female respondents. On the more negative side, one participant warned of hydrogen's "*high volatility, which would make some people think twice, or even thrice about it*" (FG9:8). Another respondent anticipated "*huge safety issues*

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with hydrogen" and raised concern around storage problems and the practicalities of piping it into homes (FG5:3). Two participants had some direct experience with hydrogen-ready boilers and demonstration projects. One respondent shared concern about the fuel being "*quite dangerous*" (FG2:5), while the other mentioned their recent experience with Gas Distribution Network Operator (GDNO), Cadent Gas, carrying out the Iron Mains Replacement Programme in their local area [237,238], with the promise of "*… hydrogen becoming a possibility in the future, that's what they've told us*" (FG9:1). Other participants were mostly familiar with hydrogen fuel cell vehicles (FG4:1, FG2:3).

Participants with limited or no knowledge and awareness of hydrogen

Nearly three-quarters of participants had less than some knowledge and awareness of hydrogen, with most of this subgroup (~74%) having no knowledge of hydrogen and familiarity only by way of name. Of note, the fuel poor group was composed of 85% having no knowledge and 15% having limited knowledge and awareness. Among older participants, familiarity with hydrogen was limited and could be traced back to high school science class. One participant acknowledged how any associations with hydrogen stretch back to their "*chemistry days*" (FG3:1) which drew agreement from fellow participants (FG3:2, FG3:3). Another respondent also reflected on their chemistry class days:

> *I would have thought most people are not really sure what it is, unless you remember being in the chemistry lab. I would have probably known if I was 16, but perhaps don't know much now* (FG5:4).

Conversely, and highlighting generational implications around hydrogen engagement, one respondent explained how their teenage son had recently mentioned that "*hydrogen could be big for the future*" (FG7:6). Among participants with a slightly higher awareness level of hydrogen, familiarity was typically linked to hydrogen for transport applications and the source of this knowledge was usually news coverage (see Appendix C). These observations broadly align with recent findings in the UK context, which suggest secondary school education, news coverage, television shows, and internet sites configure one's social representation of hydrogen and corresponding knowledge level [179].

Knowledge and awareness levels across focus groups and between genders

The results support empirical evidence in the literature which suggest males are more likely to be classified as highly knowledgeable on this topic (see Fig. 3). Males received a mean score of 2.00 compared to 1.56 for females,[11] which was explained by five male respondents demonstrating a moderate to high level of hydrogen knowledge and awareness (see Appendix D). However, across all other levels, there was no discernible differences between genders. By contrast, Smith et al. [179] reported that female respondents had a subjective knowledge level falling between "I have not heard about it before" to "I have heard of it but know nothing about it," whereas male respondents ranged one level higher, between "I have heard of it but know nothing about it" to "I know a little." However, it should be noted that the sample distribution in the aforementioned study [179] was somewhat unbalanced, with 61.2% female respondents, compared to 46.6% in this study. Otherwise, gender differences had little impact on hydrogen perceptions in our study (see Appendix D). Any provisional findings should be verified by larger and more representative UK survey studies, while the generalisability of results should be tested through cross-country comparative studies.

To investigate potential differences in levels of knowledge and awareness, the mean score for each of the seven groups was calculated and compared to results across the sample ($M = 1.79$) and groups ($M = 1.87$). This procedure showed that knowledge and awareness of hydrogen is positively associated with interest and engagement with RETs (FG2: $M = 2.50$; FG3 and FG9: $M = 2.30$), whereas participants facing fuel poverty appear to be the least informed group ($M = 1.15$). Interestingly, respondents engaged in environmental issues had a below average level of hydrogen knowledge and awareness in this study, which was contrary to expectations ($M = 1.67$). A probable explanation for some of the observed variance in knowledge and awareness levels ($SD = 0.46$) is age gaps between certain groups (see Appendix E), however, detailed analysis of socio-demographic variables is beyond the scope of this exploratory, small-sample study.

Access to sources of reliable information on hydrogen

Following the initial assessment of hydrogen knowledge and awareness, participants were asked how they would access reliable information about hydrogen in the future. Respondents typically focused on internet sources, which included Googling for "*decent scientific sites*" (FG2:2) such as Scientific America (FG3:1) and other "*trusted sites*" (FG8:6). Some respondents suggested searching relevant online forums to "*see what people are saying*" and to "*hear people tell their story*" (FG5:5). Two professionals mentioned specific options such as the Institution of Engineering and Technology (FG2:2) and the Buildings Services Research and Information Association (FG2:5). One participant also suggested looking to see "*what local councils are doing on their websites*" (FG8:6), while another recommended finding "*someone who already has one of these systems in their house or has taken part in a trial to see how they fared with it*" (FG5:2).

Along similar lines, a participant engaged in environmental issues explained how they "*would probably Google and try to find accurate information, hopefully which is backed by evidence too*" and "*also look at what the local council says*" (FG8:9). In the eyes of one respondent, the sources should be from trusted departments including "*government websites and the office of national statistics, which promote and spread knowledge to the people*" (FG10:2). Following this comment, another participant offered an alternative approach, "*I'd try to access information from my energy provider; they might be the right ones to get the information from*" (FG10:3).

[11] Lowest knowledge and awareness = 1; Limited knowledge and awareness = 2; Some knowledge and awareness = 3; Higher knowledge and awareness = 4.

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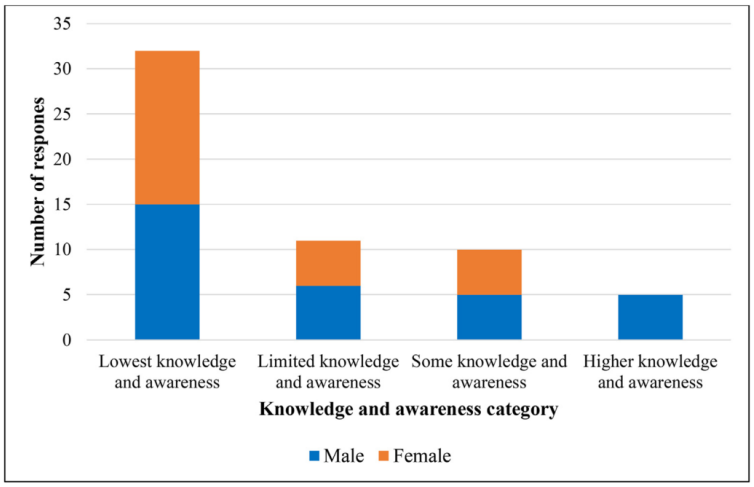

Fig. 3 – Breakdown of knowledge and awareness levels across focus group sample by gender.

Across the sample, the most cited sources for accessing reliable information on hydrogen included scientific websites, government websites, professional online platforms, local councils, and energy providers. In sum, government, media, energy providers, professional institutes, and local councils have a clear role to play in disseminating clear and meaningful information to the public. At the same time, there will be different preferences and tendencies across parts of the public when it comes to deciding which platforms to access and trust. For a growing part of the population, internet sites are likely to be the most immediate source of information. However, the activities of local councils may prove critical to spreading information about hydrogen in a more direct and impactful way at the grassroots level [239].

Consumer perceptions of the twin-track approach

Following the first round of information provision (see Table 4), participants were presented with a follow-up poll question: *How do you feel about the government's twin-track approach? (with a role for both blue and green hydrogen production)*. As the focus groups were conducted prior to the announcement of the British Energy Security Strategy in April 2022, participants understood that both production pathways would be implemented, however, there was no specific guideline was communicated regarding the potential share of blue and green hydrogen production.

Responses were measured on a five-point Likert scale, ranging from (1) *very opposed* to (5) *very supportive*. 93% of participants completed the poll (N = 54), with one-third positioning themselves as *very supportive* of the twin-track strategy. The most frequent position was *somewhat supportive* (N = 24), which accounted for nearly 45% of the responses. Of the remaining responses, participants were *somewhat opposed* (N = 5), followed by *neutral* (N = 4), while only one respondent proved *very opposed*. The next sections review the explanations given by respondents for these respective positions.

Positive perceptions of the twin-track approach

Positive views of the twin-track approach stemmed from seeing it as a "*logical*" choice and "*calculated decision*" (FG9:2), which may help maintain convenience for end-users, while minimising disruption (FG5:2, FG6:3). This was viewed as a "*welcome development*" (FG9:5) and "*good news*" (FG4:2), wherein the government was seen to be "*taking the initiative*" (FG9:2) to address climate change (FG3:2, FG4:1, FG4:3, FG10:2, FG10:4). One participant concluded that "*it makes perfect sense they would target heavy industry first and might rely on blue, but eventually look to go all green*" (FG3:3).

Other positive perceptions, albeit with more moderate levels of support, were formed around seeing the twin-track strategy as aligned to potential energy security benefits and cost reductions to consumer bills (see Appendix F). For example, a Scottish participant saw it as "*positive news and a step in the right direction, if they're going to be getting away from grey hydrogen*" (FG5:5). However, several participants highlighted the need to understand a lot more about both cost and environmental impacts, either requesting or demanding more information to consolidate or strengthen their support. In the words of one respondent, what matters most is "*how cheap it will be for the average person, at the end of the day*" (FG7:1).

Despite some consensus that the twin-track approach may prove a more full-proof strategy for deploying hydrogen, there was underlying scepticism about the benefits of doubling down on a blue hydrogen production pathway to help reach net zero [62]. For example, one respondent inquired about "*… how fast would the transition go, from grey to blue to green; what's the timescale to eventually being totally green, if possible?*" (FG3:2). Although several participants declared themselves to be *somewhat supportive* when answering the poll, upon further

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inspection (i.e. probing from the moderator) this positivity was often contingent on the Hydrogen Strategy supporting environmental benefits and cost savings to consumers. Conservatively, it may be concluded that positive perceptions of the twin-track approach were somewhat inflated in the poll results compared to articulated responses, which leaned more towards neutral, but otherwise hopeful perceptions. In response, subsequent research could employ a seven-point Likert scale to better differentiate response patterns.[12]

Neutral perceptions of the twin-track approach

Participants who were more neutral or undecided about the merits of the Hydrogen Strategy felt that the twin-track approach was indecisive; referring to it as "*half-hearted*" (FG8:3, FG9:1), "*half-baked*" or a "*half-way house*" (FG3:1) One participant associated the strategy with the shortcomings of transitioning to electric vehicles, "*… if they are really going to invest in it, they have got to do it fully … it's like with electric cars, they've only done it half-way*" (FG2:3). This response was especially noteworthy since the respondent was *somewhat supportive*, as opposed to neutral or opposed to the twin-track approach. Such framings underscore the need for the government to pre-empt consumer resistance on environmental grounds – or due to negative association with past policy failures such as diesel cars [240] or the Green Deal [241] – by justifying the legitimacy of committing to a blue hydrogen pathway. Another participant expressed scepticism over the legitimacy of community benefits promised by the hydrogen transition:

> *The twin-track approach seems like a half-hearted situation and from experience of what I'm seeing here in Teesside, it's the opportunities that the business world and the private sector see for their own benefit rather than from an environmental point of view. I sound very anti-capitalist, but that's not the point. It just seems that investment goes into something and then ends up in someone else's private pocket* (FG8:3).

Additionally, some participants were concerned about heightened risks to early adopters, the profit motives of private companies, and the need to address a vast array of 'unknown' factors (see Table 6).

Negative perceptions of the twin-track approach

Participants *somewhat opposed* to the strategy objected more strongly to the use of fossil fuels, viewing hydrogen as potentially wasteful compared to using electricity directly from the grid. Red flags were also raised regarding safety concerns and mistrust in the government (see Table 6). In terms of safety perspectives, consumers worried about the explosive risks of hydrogen and the suitability of an orange flame, as opposed to the familiar blue flame (FG1:4, FG7:1, FG9:3). One respondent also admitted to being unsure about "*getting on a plane that's fuelled by hydrogen*" (FG7:6), reinforcing how public perceptions of other end-uses such as transport applications may impact the social acceptance of domestic hydrogen.

Only one participant (FG8:1) was *very opposed* to the UK Hydrogen Strategy in general, based on ideological grounds rather than an assessment of the twin-track approach per se. In their view, the short video – which featured statements from the Head of hydrogen projects, Northern Gas Networks (Tim Harwood), former UK Business and Energy Secretary (Kwasi Kwarteng) and a Chief Scientist from Greenpeace (Dr. Doug Parr) – was judged to be "*very big brother*" and one-sided, representing "*all men … telling you what to do*" (FG8:1). This respondent shared an important perspective which resonates with the notion of internalising distributive, procedural and recognition justice [242] into the decarbonisation agenda, as a prerequisite for facilitating social acceptance [243,244]:

> *If you are going to change things, people need to be brought along for the ride and educated. They need to be bought in, to love and be included in it … the fundamental element of change is you have to bring people along and if you don't demonstrate diversity and you don't include people, then you've lost 80% of your audience without even trying* (FG8:1).

This commentary received degrees of acknowledgment and approval from some members of the focus group. Notably, public participation, established on foundations of deliberation and inclusion [245], has been linked to mobilising an accelerated and just energy transition [246–248], which the above statement attests to.

Perceptions of the twin-track approach across focus groups

Given that 78% of respondents expressed underlying support for the twin-track approach, split between 39% *very supportive* and 46% *somewhat* supportive, there was minimal quantitative data representing neutral or negative perceptions. Notwithstanding, some notable patterns emerged when analysing the poll results in relation to focus group categories (see Fig. 4).

Differences in consumer attitudes towards the twin-track approach were measured by calculating the mean score for each group (Scale 1–5: Very opposed – Very supportive), as described in Appendix F. Foremost, citizens living in fuel poverty or facing high levels of fuel stress ($M = 4.67$), and owners of solar PV panels and smart home technologies ($M = 4.55$) expressed the strongest level of support for the twin-track approach. For the former group, hydrogen was largely welcomed, with hopeful visions for improving the environment and lowering energy costs in the long-term. The latter group perceived a scaling up of hydrogen production – whether blue or green – as a positive step towards advancing the net-zero agenda.

Next, citizens living in industrial towns expressed the strongest level of support for the twin-track approach ($M = 4.40$), perceiving hydrogen as a stimulus for reinvigorating industrial areas and delivering economic growth, as well as local jobs. Convergence between participants experiencing fuel poverty and those living in industrial towns may be explained by the fact that several fuel poor respondents were from large cities in Northern England, namely, Manchester ($N = 6$), Leeds ($N = 1$) and Liverpool ($N = 1$).

[12] In this study, a five-point Likert scale was deliberately chosen to help maximise responses rates and for efficiency purposes (i.e. minimising time spent on the polls to enable richer discussion).

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Table 6 – Critical concerns and reservations regarding the twin-track approach.

Participant	Position	Illustrative quotations
FG1:2	Somewhat opposed	• *I'm somewhat opposed to this idea of a two-track system. Why can't we just go for the green? I don't understand why we have to do the blue and green? If green is the best option, why are we somewhere in the middle?*
FG1:5	Somewhat opposed	• *Why don't we just go with the best environmental option? I understand that there's a cost difference … but I think for me it's about trusting the government, that they will do right by us and by the planet. And I don't quite trust what they'll do because they'll always have another agenda that's trying to be achieved, other than looking after us and the planet. So, that's why I'm somewhat opposed, but I might feel that way about anything the government comes up with.*
FG3:1	Neutral	• *… well, the mix is a half-way house, and it needs to eventually be transmitted to fully green! But it makes sense the hydrogen strategy. It's logical that industry is the primary use … a transition period where the boilers are made to run on both, that's critical. It has to happen.*
FG7:5	Somewhat opposed	• *I was opposed to the twin-track approach because I don't see the point. Why not go straight for the green, if you're going to do it?*
FG8:2	Somewhat opposed	• *It's still burning stuff though, isn't it, unfortunately. And that's what we're trying to avoid … it's still burning stuff and it doesn't matter what spin you put on it. In some parts of the country, there is no green … it's a fudge like E10 fuel … like buying diesel cars in 2009. CCS is sweeping what we burnt under the carpet.*
FG9:1	Somewhat opposed	• *I wouldn't be happy to move into something which is half-hearted … I think more needs to be done to move towards a more environmentally solution. I think it's crazy when you've got solar power and wind and you're using that power to generate hydrogen. So, it doesn't seem feasible to me, and it does worry me about it being piped into my property. I just feel that it's using large amounts of electricity and still using fossil fuels … I don't see the point. I just don't feel it's the way to go, especially with the blue hydrogen.*
FG9:3	Neutral	• *I was kind of on the fence. I'm not used to the orange flame. Would that pollute? What are the risks there? The price will be high at first but then might come down, so will the early adopters or first testers be like the scapegoats?*

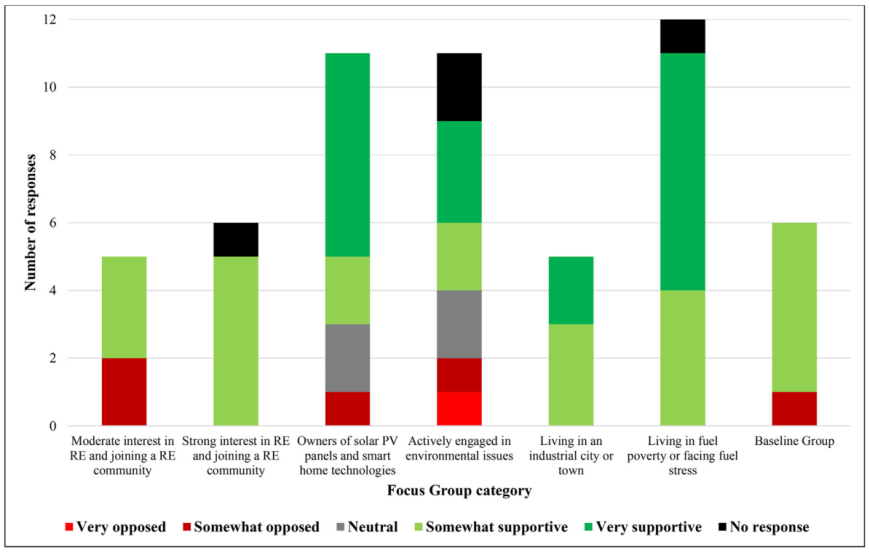

Fig. 4 – Consumer attitudes towards the twin-track approach across focus groups.

Divergence in opinion was observed between the two groups from Marston Moretaine, Bedfordshire, with the more renewably engaged group expressing stronger support for the twin-track approach ($M = 4.00$). This discrepancy fits with expectations and suggests that familiarity with onshore wind farms and solar PV, and environmental protection may bolster the potential for hydrogen acceptance. Additionally, it is noteworthy that participants actively engaged with environmental issues presented the widest range of responses and, by comparison, the lowest levels of *very supportive* or *somewhat supportive* positions (60% of responses compared to a mean of 85% across the sample).[13]

Tellingly, neutral and negative perceptions were largely attributed to scepticism or disapproval concerning the inclusion of blue hydrogen as a decarbonisation pathway.

[13] The Pilot group (FG1) also recorded 60% for this answer category.

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Notwithstanding, the environmentally engaged group shared a similar level of overall support for the twin-track approach as the baseline group ($M = 3.70$). While these findings remain exploratory due to the limited sample size, there is clear strategic value in seeing whether these results can be validated, or possibly become more pronounced in some ways when dealing with a larger dataset.

Public perceptions of hydrogen futures

Near the end of the focus group, participants were asked to complete a final poll question, for which the response rate was 100%: *Overall, how do you feel about hydrogen homes being part of the UK's energy future?* Alongside the poll data, several respondents justified the rationale behind their viewpoints (see Appendix G). This section systematically reviews consumer perspectives on this scenario according to key themes and concludes by comparing results across focus group categories.

Environmental benefits and intergenerational climate justice

The main driver of support for domestic hydrogen futures across the sample was recognition of potential environmental benefits, which were described by members of one focus group as the need "*to go greener*" (FG1:1), "*… take us a step closer to being carbon neutral*" (FG1:2) and "*make a big difference to climate change*" (FG1:3). Elsewhere hydrogen was viewed as "*the way forward to get carbon neutral and sustainable*" (FG4:2) and an effective means for discontinuing "*the carbon intensive lifestyle we've been used to.*" (FG9:6). Among owners of solar panels and smart home technologies, support stemmed from the environmental promise of hydrogen, and moreover, green hydrogen. The theme of intergenerational climate justice was also discussed, with one respondent calling hydrogen "*a step in the right direction*" and describing themselves as "*ready for a change*" to "*something much more sustainable and safer for the environment, for the generations to come*" (FG9:3). Similarly, a fuel poor respondent saw hydrogen as an "*opportunity to do something better for the planet … not just our generation, but future generations*" (FG6:2). Such remarks were greeted with approval by fellow participants.

Disruptive impacts and energy efficiency

In addition to environmental benefits, positive responses to hydrogen centred on its perceived potential in minimising the disruptive impacts of residential decarbonisation, while promoting efficiency gains for household heating. These arguments align closely to what advocates typically cite as the main advantages of hydrogen, compared to alternative technologies such as heat pumps [249,250]. This sense of technology optimism (see Table 7) reflects a scenario in which low-carbon hydrogen appliances provide a like-for-like replacement existing boilers and hobs, thereby minimising disruption to the consumer [249–251].

Cost concerns, risk factors and information deficits

Reservations concerning domestic hydrogen stemmed mainly from the desire to know more about the personal impacts of the switchover (see Table 8). However, an underlying information deficit often translated into greater perceived risks. A fuel poor participant expressed concerns over the "*unknowns*" of cost factors as well safety aspects, asking for greater clarity on these areas (FG6:1), while a fellow respondent stressed the need for transparency on cost factors (FG6:2). Similarly, the initial response in Focus Group 9 cited the need for "*more information on cost, disruption, and safety*" (FG9:1). In several cases, environmental concerns were trumped by financial concerns, which emerged as common theme across focus groups:

> *Although I am concerned about the environment, I hate to say it, but I am most concerned about myself and my family. So, it's all about how it affects me really, and would it be worth my while and how much might I potentially save* (FG3:3).

This finding is consistent with the Schwartz's theory of value contents and structure [252,253], wherein hedonic values such as personal comfort and financial security outweigh more self-transcendent or collective values linked to environmental protection and intergenerational climate justice [254]. In the words of one respondent, "*… even though I want to make a positive change, I don't want to do it at a big cost to me*" (FG6:2).

Table 7 – Positive expectations for minimising disruption and maximising energy efficiency.

Participant	Illustrative quotations
FG1:4	• *Whenever we've had a new gas boiler at home in the past, we've found it to be much more efficient than the old one. I would be hoping hydrogen would be as efficient or more efficient than what it replaces.*
FG2:1	• *… it will operate the same as the gas does, then to me you don't need to have your house tore apart.*
FG2:3	• *… because if you're trying to get people to adopt a brand new technology that's completely alien to them, most people won't do it. It will take years for that to happen, whereas this is fairly normal, with minimal pain or disruption. If there's a technology that allows us stick with the bulk of what we have: we don't need to change our radiators, we don't need to learn to cook differently, we don't need to put new pipes in; all we need to do is switch out a boiler and switch out a hob essentially.*
FG5:3	• *It's opened my eyes this forum tonight and especially the [second] video. That house looked pretty normal. I don't know what I expected like a big tanker outside maybe or a cannister or something, but it didn't look intrusive. So, I'm feeling a lot more positive about it than I probably was before.*
FG7:6	• *I've heard about heat pumps, but this seems quite straightforward in a way. You are replacing gas with hydrogen coming through the pipelines and that's why I'm supportive of it. I understand it a lot more than I do heat pumps. Although there might be a short-term disruption, you haven't got a big thing hanging on your wall like a heat pump. So, you wouldn't really notice a difference.*

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Table 8 – Reservations concerning the proposition of hydrogen homes.

Participant	Illustrative quotations
FG1:3	• *I'm somewhat supportive but before I could be fully on board, I would need to know a lot more about it.*
FG5:1	• *For me, it's all about hearing from real people who are part of the trials and how they lived day-to-day with their family using hydrogen, so they can feed back to us and give us an honest view of what it's like moving over to that new system. For me, that is the one thing that would convince me to change.*
FG5:3	• *Teething problems like safety issues that might be encountered once this in place and people have real life experiences.*
FG5:4	• *We all need more education on it and that's what the videos helped with, but probably we still need to know a lot more about it.*
FG5:5	• *Yeah, the concept is good … see how the trial goes like and how it rolls out, but sure, cost is the main factor.*
FG6:2	• *I think lack of information is probably the big thing that hinders me from saying I'm extremely willing; lack of information on price … most questions will be around the finance of it because that's where we're out of pocket to begin with.*
FG6:3	• *You would need to know a lot more information. For example, if you provided a sheet that said these were the costs here, that would make my mind up about how supportive I am … it's the cost that would be the main factor for myself. The costs and also the safety aspects of it all, is it safe.*

Energy injustice and trust deficits

Among environmentally engaged participants, two respondents (FG8:2, FG8:3) perceived hydrogen futures through a neutral lens. Notwithstanding, the critique of one participant suggested a degree of resistance based on a view of systemic injustice within the UK energy system:

> *Energy shouldn't be for-profit … how can you make profit from people's suffering? The environment is suffering, and the usual suspects are profiteering at the end of the day, and that seems to be a big problem … and how do you basically change the model so it does become more like the NHS … it's centrally funded and it has those values as its core principles … I'll pay for it when I'm comfortable that I've been able to make the right decision … that's why I've turned down previous grants that were free* (FG8:3).

Additionally, the same respondent relayed personal experience of rejecting government grants for home retrofits based on professional knowledge of the trade. Specifically, grants were regarded as flawed and inadequate, since choices are ultimately taken by the installer, which may discriminate against low-income households:

> *… if the installer doesn't see a significant profit, they won't bother to do it. So, the lower income households and smaller households get pushed aside if there is a choice between ten small properties and three larger properties, the private installer will go for the three* (FG8:3).

In other focus groups (FG9, FG10), respondents also stressed the importance of cost factors in relation to distributional justice and geographical exclusion:

> *It's very interesting to hear that there are different kinds of hydrogen production. What's disappointing is that in my part of the country it doesn't look like it is going to happen in the foreseeable future* (FG7:3).

This observation underlines the importance of unpacking how the spatial dynamics of the hydrogen switchover and geographical exclusivity may impact social acceptance [63].

Energy cultures and rejection of domestic hydrogen

Although an isolated case in this study, one participant perceived hydrogen as opposing their preferred energy culture [255,256] due to potential risks of being an early adopter or 'guinea pig': "*I don't want to pay for someone else's experiment that may or may not work. I am trying to be energy independent*" (FG8:2). Research on community energy projects [257] and emerging energy cultures in the UK [256,258] remains nascent, therefore, it is challenging to predict what proportion of the population may share similar desires for energy independence, and whether this broadly correlates to residents living in remote locations or hard-to-treat properties [259,260]. An important aspect of supporting a socially acceptable transition [63] lies with better understanding the energy needs of communities located off-grid (~15% of the UK housing stock) [261].

Perceptions of domestic hydrogen futures across focus groups

Based on the poll results, consumers proved highly receptive to the idea of hydrogen homes forming part of the UK's energy future (see Fig. 5 and Appendix G), with around 40% (N = 23) and 53% (N = 31) answering *somewhat* and *very supportive*, respectively. This finding suggests the proposition of low-carbon hydrogen heating and cooking appliances may be viewed favourably across different segments of the UK population, especially when information provision helps enable a more educated perspective.

The highest level of support for domestic hydrogen was observed among respondents with strong interest in RE and in joining a RE community, and citizens facing fuel poverty (M = 4.80), which equated to near unequivocal support. Participants engaged with renewable energy and smart home technologies looked favourably towards the vision of hydrogen in a net-zero future (M = 4.50) (see Appendix G). Overall, hydrogen was well received by most respondents in these groups owing to shared perceptions of environmental benefits and positive framings around intergenerational climate justice [262,263] (see Fig. 5).

By comparison, respondents actively engaged in environmental issues recorded the lowest response (M = 3.90), seemingly due to underlying reservations concerning the suitability of blue hydrogen, and likely owing to associated factors, such as lack of trust in the government and energy

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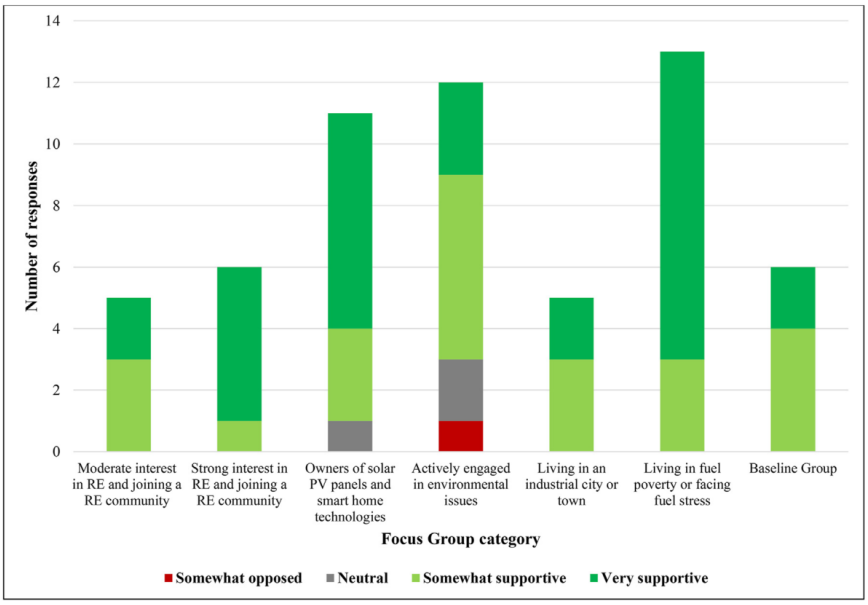

Fig. 5 – Consumer perceptions of hydrogen homes as part of the UK's energy future.

companies for meeting net-zero ambitions (see Fig. 5). Similarly, the baseline group recorded a comparatively lower score ($M = 4.30$) than the remaining focus groups, which suggests that hydrogen acceptance is lower when controlling for factors related to group membership. Overall, the results suggest that engagement in renewable energy, or experiencing fuel poverty may act as critical drivers of domestic hydrogen acceptance.

Consumer messages to stakeholders shaping the hydrogen transition

To conclude the focus group sessions, participants were asked to relay *one key message* to the actors and stakeholders of the hydrogen transition, and relatedly, asked the following: *Imagining a future where you have to choose about using hydrogen, what would you like to know most of all before making a final decision?*

This question triggered a range of responses from around one-third of the sample. The need for increased education and information was cited a total of 9 times, with specific requests for more information from the government and at the grassroots level (see Fig. 6). The other most frequent cited factors included financial implications to households, and impacts related to the environment and sustainability, which included the safeguarding of future generations. The following factors were also singled out by different respondents: appliance performance, energy security, the logistics of boiler replacement, and the quality of hydrogen gas compared to natural gas (see Table 9). Notably, one respondent from the industrial towns group called for "*easy information for people to access which shows a comparison between natural gas and hydrogen*" (FG5:1). This was envisioned as follows:

> *Here is your boiler: here is the initial cost, how much could save, and the carbon footprint reduction. So, a very easy way to compare the shift, something more visual for people so they can see the impact it would have* (FG5:1).

Overall, responses underlined the extent to which the importance of adequate information provision and educational campaigns cannot be overlooked if social acceptance is to transpire (see Appendix H).

Meta-inferences and statistical tests

Previously, we examined hydrogen knowledge and awareness levels across the sample and between genders, also reported consumer preferences for accessing sources of reliable information on hydrogen. This aspect of the study was further emphasised by realying consumer messages to stakeholders shaping the hydrogen transition. As a way of further exploring the relationship between knowledge and awareness and hydrogen perceptions, statistical analysis is performed to see if significant associations exist between variables examined in this study.

Kendall's tau-b (τ_b) correlation test was conducted to explore relationships between variables. Kendall's tau provides an alternative non-parametric test to the Pearson's

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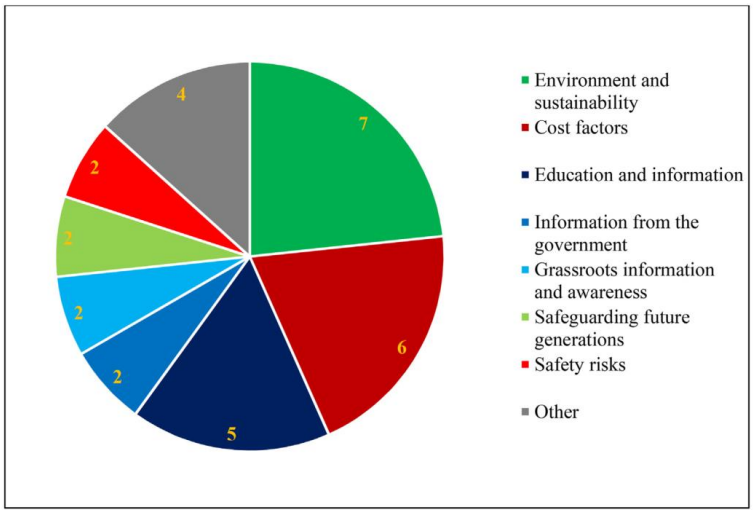

Fig. 6 – Consumer perspectives on informational aspects of the domestic hydrogen transition.

Table 9 – Consumer perspectives regarding the need for specific information on domestic hydrogen.

Participant	Illustrative quotations
FG1:5	• *It needs to be objective, the information – that would be a better approach than greenwashing.*
FG2:1	• *I would want to know that it's sustainable and long-term … and I would want to know about the energy savings … how long is your plan for this? Is it going to be funded and properly moved forward?*
FG2:3	• *I would want to know that it's fully backed and full-proof. Companies are private and can do whatever they want, but if it's backed by the government, I'd be on board or more willing. If I'm going in, I want to know that they're all-in and I'm not the one taking all the risk and funding their venture … does it really live up to the hype or it is going to be another fad? Does it really do what it promised to?*
FG2:6	• *I think it's important to know how hydrogen would affect the UK and whether it would make us more self-sufficient, as opposed to having to import foreign gas. Because look at the price hikes in gas at the moment and everything that's going on with Ukraine.*
FG4:2	• *Would there actually be places where you can go and see it in demo homes? Would the general public have access to see first-hand, to see it and feel it, and use it for yourself?*
FG6:3	• *I didn't know it was possible to have hydrogen in your home. It's been interesting and eye-opening, and I think this is where the future is heading. We need more information like this where we can make up our minds and decide if it's suitable for us, as a family and in our community.*
FG7:3	• *It also depends on the quality of gas that's put out. I remember when we changed from town gas … the natural gas delivered a lot less heat and energy … so that would be something that we'd definitely need to know.*
FG7:5	• *Do you have to put a new one [boiler] in when they say, or do you wait for your existing one to be worn out?*

product-moment correlation coefficient, which is recommended over the Spearman rank-order correlation coefficient (another non-parametric option) for measuring the strength and direction of association between two variables of interest [264,265]. Kendall's tau should be applied when the sample size is small, has many tied ranks, and there is an expected monotonic relationship between variables [264,266,267], which is the case in this study. Statistical tests were carried out for most of the sample, following a high response rate to poll questions (N = 54).

Contrary to evidence in the literature which suggests scepticism towards HETs may be associated with an underlying knowledge or experience gap [82,143], this study observes no significant association between knowledge and awareness and support for domestic hydrogen futures ($\tau_b = .095$, $\rho = 0.445$) or broader hydrogen acceptance ($\tau_b = -0.182$, $\rho = 0.117$). However, knowledge and awareness appear to shape perceptions of the twin-track production approach to a degree. The knowledge and awareness variable[14] showed the following descriptive patterns (see Appendix I), which informed the statistical results: Low knowledge awareness (N = 29, $M = 4.31$); Limited knowledge and awareness (N = 29, $M = 4.10$); Some knowledge and awareness (N = 10, $M = 3.80$); and Moderate to high knowledge and awareness (N = 5, $M = 3.00$). A weak to moderate, negative correlation was observed between hydrogen knowledge and awareness and perceptions of the twin-track approach, which was statistically significant: $\tau_b = -0.344$,

[14] Converted from the original Scale of 1–4 to Scale of 1–5 by multiplying by a factor of 1.25.

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$\rho = 0.004$ (Bootstrap 95% confidence intervals: −0.117 to −0.531). It can be inferred that scepticism regarding the twin-track approach may prove more likely when consumers are older, highly educated males who are environmentally engaged, and not experiencing fuel poverty.

Next, Kendall's tau was performed to test the relationship between the following variables: consumer attitudes towards the twin track approach, (2) consumer perceptions of domestic hydrogen futures, and (3) hydrogen acceptance (the mean score of the former two variables). All three relationships proved significant at the 0.01 level (2-tailed), with the strongest relationship observed between the twin-track approach and hydrogen acceptance, followed by domestic hydrogen futures and hydrogen acceptance (see Table 10). By contrast, the positive association between attitudes towards the twin-track approach and perceptions of domestic hydrogen futures was more moderate. This finding adds weight to the qualitative evidence by suggesting mostly marginal support for the twin-track approach among respondents, which may partially negate support for domestic hydrogen. Fig. 7 visualises these findings based on the aggregate data of the study (see Appendix I), while Table 11 concludes this section by deriving meta-inferences from the mixed methods results.

Table 10 – Kendall's tau results for measures of hydrogen perceptions.

	Twin-track approach	Domestic hydrogen futures	Hydrogen acceptance
Twin-track approach	1		
Domestic hydrogen futures	.496[a,b]	1	
Hydrogen acceptance	.868[a,c]	.749[a,d]	1

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Bootstrap 95% confidence intervals: 0.280–0.676.
[c] Bootstrap 95% confidence intervals: 0.808–0.921.
[d] Bootstrap 95% confidence intervals: 0.635–0.845.

Discussion

This paper presents mixed methods insights on consumer perceptions of domestic hydrogen futures in the UK context, with a focus on public knowledge and awareness of hydrogen, and the government's Hydrogen Strategy, specifically, the twin-track production approach. Analysis and comparison of focus group transcripts, alongside statistical analysis of poll data, provide integrated findings on hydrogen perceptions. The findings speak to the importance of raising public awareness and consumer engagement to help alleviate scepticism, concerns, and preconceived notions about hydrogen which could otherwise stifle a potential transition to hydrogen homes. The results also caution that much of the public is yet to engage with hydrogen beyond a surface level, if at all, which should put the government and industry on red alert about diffusing hydrogen into the public consciousness, in alignment to the energy security, fuel poverty, and net-zero agendas.

To alleviate scepticism and concerns, information campaigns should ensure greater transparency regarding the benefits, costs, and risks of the transition, with clearer communication on the timeline of the potential roll-out and

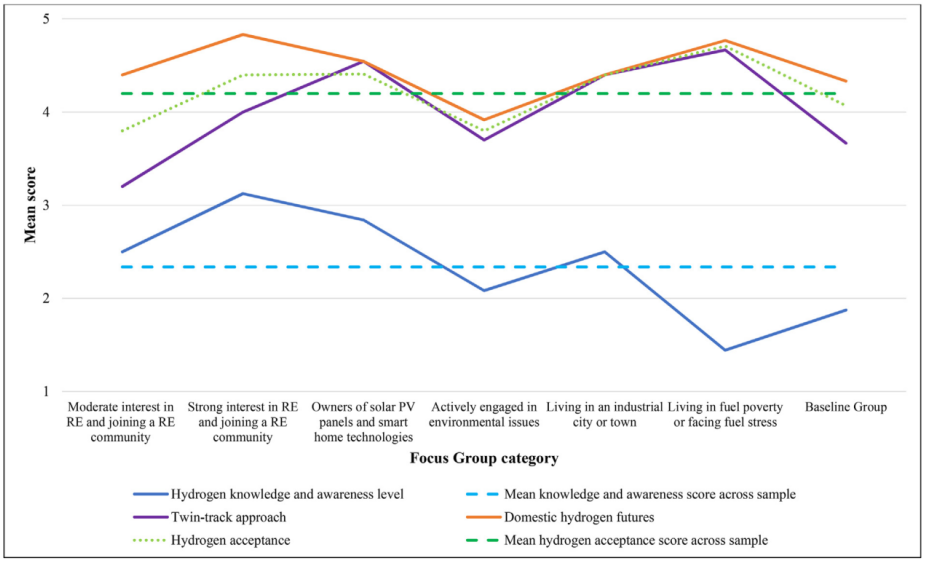

Fig. 7 – Measure and comparative assessment of domestic hydrogen acceptance across focus groups and sample.

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Table 11 – Meta-inferences on hydrogen perceptions from mixed methods, multigroup analysis.

Research question	Quantitative inferences	Qualitative inferences	Meta-inferences
RQ1 What is the existing level of hydrogen knowledge and awareness among UK consumers? (RQ1a); and what preferences do UK consumers have for information dissemination on hydrogen? (RQ1b)	• Limited or low levels of knowledge and awareness across most of the sample, with younger respondents appearing less informed • Hydrogen knowledge and awareness is positively associated with ownership of solar PV panels and smart home technologies, and broader engagement in renewable energy • Younger citizens facing fuel poverty are mostly unfamiliar with hydrogen	• Existing hydrogen knowledge and awareness typically stems from high school science education (especially for older respondents) and media coverage (television and internet) • Hydrogen for transport applications is more familiar than use for domestic heating and cooking purposes	• Hydrogen, particularly for domestic applications, is yet to enter the public consciousness • Social representations of hydrogen remain relatively malleable for most consumer segments • UK citizens appear largely receptive to learning more about hydrogen and express a proactive attitude towards information dissemination • Hydrogen perceptions may be shaped positively by targeted education campaigns led by the government, business, and industry • Parallel information dissemination and consumer engagement is required through grassroots channels to build market confidence and trust • Consumers request further information on environmental and sustainability aspects, cost factors, and safety
RQ2 What perceptions do consumers hold towards the UK government's twin-track approach entailing blue and green hydrogen production pathways?	• Close to half of the sample express a *somewhat supportive* position for the twin-track approach, while one-third appear *very supportive* • Support levels are highest for respondents facing fuel poverty, living in industrial towns, and owning solar PV panels and smart home technologies, whereas participants actively engaged in environmental issues expressed comparatively lower levels of support	• Support stems from seeing the UK Hydrogen Strategy and the twin-track approach as a positive milestone and step towards delivering net zero • Concerns and scepticism are attributed to perceptions that the twin-track approach is non-committal to a renewable future and may lock in reliance on natural gas	• Support for the twin-track approach has a moderate positive effect on consumer perceptions of domestic hydrogen futures, and a strong, positive effect on underlying hydrogen acceptance • Location and income may shape approval rates for the twin-track approach, with industrial areas and households experiencing fuel poverty appearing more inclined to support the government's vision • Engagement in environmental issues may provoke concerns over the legitimacy of blue hydrogen and thereby diminish hydrogen acceptance • The government should take steps to justify the environmental grounds for the twin-track approach and publicise the rationale to the wider public, through national media coverage and other outlets such as non-governmental organisations

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Table 11 – (*continued*)

Research question	Quantitative inferences	Qualitative inferences	Meta-inferences
RQ3 How do consumers perceive the prospect of domestic hydrogen as part of the country's low-carbon energy future?	• Respondents express overwhelming support for hydrogen in the UK's energy future, with 31% answering *very supportive* and 62% *somewhat supportive* • Support levels increase with interest in renewable energy, and conditions of fuel poverty	• A lack of education and information is cited as the main barrier to social acceptance, with respondents stressing the need to increase clear and transparent information on domestic hydrogen • Hedonic and egoistic values related to financial factors and material needs typically outweigh environmental concerns when considering the adoption of hydrogen appliances and support for the transition	• Support for domestic hydrogen is higher than for the twin-track approach across the sample and for most focus group categories, and thereby has a stronger positive association with hydrogen acceptance • The prospect of converting parts of the UK housing stock to hydrogen homes should be coupled more strongly to the potential socio-economic benefits of the transition • Key actors and stakeholders should advance a strategic communication campaign which better situates the environmental benefits of hydrogen and the importance of net zero within the broader discussion of energy security and fuel poverty • Alternative options for decarbonising homes such as heat pumps and district heat networks should be advocated for, in parallel, when promoting the prospect of hydrogen homes • Special attention should be paid to households located in rural areas, especially off-grid, as well as fuel poor and vulnerable parts of society, as a means for enacting a fair and socially acceptable pathway for residential decarbonisation

emissions reduction. In response, social marketing and education campaigns should communicate the positive socio-economic aspects of hydrogen [60], while informing consumers about core safety and environmental credentials [19,66]. Optimally, such campaigns should account for specific challenges and opportunities associated with different geographical areas [19,160,190], socio-demographic groups [64,178,268], energy cultures and attitudes [66,255,269].

It follows that domestic hydrogen acceptance will rest on how public knowledge and awareness shape consumer perceptions of hydrogen's environmental credentials in relation to respective production pathways, among a myriad of other key factors. Underlining this critical point, one respondent expressed a position which may reflect certain segments of UK society, and will need to be internalised by the government when delivering their long-term hydrogen strategy:

> *For me, it was hearing about blue hydrogen and the reliance on fossil fuels, which I wasn't aware of. For me, we need to be moving to constant renewable or green energy to give us that hydrogen. So, that surprised me from all the information from tonight* (FG5:1).

While there is some encouragement for and wider openness to pursuing the twin-track strategy, parts of society are likely to call for stronger commitment towards a greener pathway. Scepticism over blue hydrogen appears more probable when consumers are actively engaged in environmental issues. Similarly, respondents with awareness of UK energy and environmental policy may question the merits of the twin-track approach, potentially viewing it as non-committal to decarbonisation efforts. Negative perceptions of the twin-track strategy also tie into an emerging awareness of intergenerational climate justice, which may prove more prevalent among families with grandchildren. Nonetheless, personal considerations around cost factors typically supersede concerns around climate change and the environment. Consequently, when requesting critical information on domestic hydrogen, consumers principally cite cost factors and safety implications, and in some cases, environmental impacts.

At a general level, the public is encouraged by the launch of a national hydrogen strategy, perceiving it as a positive measure for climate change mitigation and energy security. However, public support for hydrogen homes is largely contingent on cost savings for consumers, and to a lesser degree, rests on the contribution of hydrogen to net zero. The potential relevance of this finding is especially noteworthy, given that environmental issues appeared to resonate strongly with participants across all focus groups [270]. Finally, evidence also suggests that respondents recognise the importance of a fair

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hydrogen transition. Most notably, citizens value safeguarding the needs of vulnerable members of society throughout all stages of the switchover. At the same time, there is growing awareness that "*a more holistic approach*" is needed to offset the pitfalls of "*a one-size-fits-all approach*" (FG1:5).

This research supports active engagement with different segments of the population, as a mechanism for facilitating a more inclusive and insightful debate on the implications of hydrogen production pathways and the deployment of hydrogen homes [178]. Critically, the notion of competing or complementary hydrogen production pathways must shift beyond academic and policy debates [107,112,271,272] by entering the public discourse in a meaningful way, so that propositions such as the twin-track approach can be understood and responded to. For this to transpire fully, policymakers, industry actors, and other key stakeholders must first dedicate sufficient resources to moving the dial on hydrogen knowledge and awareness. Until this happens, there is a risk that the twin-track approach may be viewed as somewhat incompatible with supporting a net-zero society, thereby undermining conditions for domestic hydrogen acceptance.

As a starting point, information campaigns should communicate the potential merits of combining two or more hydrogen production pathways, thereby dispelling misconceptions among parts of the public that a multi-pronged production approach is non-committal. Should a negative social representation of the twin-track approach manifest within the public consciousness, there is palpable risk of consumer resistance towards the domestic hydrogen switchover, which may undermine the broader transition to a national hydrogen economy. As Betsen et al. [31:10] argue in the Norwegian context:

> Lacking or ambiguous communication concerning projects using grey, and to a certain degree blue hydrogen, could lead to an opinion backlash regarding new hydrogen technologies, as well as reduced trust in politicians and companies if the proposed projects do not align with the public's expectations of emission reductions.

In parallel, policymakers and GDNOs must achieve their intended goals of demonstrating the viability of hydrogen home appliances across parts of the housing stock, while engaging local communities in the transition process and, as underscored within this study, factoring consumer heterogeneity into the development of hydrogen village trials.

Conclusions

This study focused on several key aspects of domestic hydrogen acceptance, including consumer preferences regarding hydrogen production pathways, the logistics of the switchover, and informational processes. The results align with the wider literature in several ways: (1) relatively low levels of hydrogen knowledge and awareness were reported among the sample; (2) the main source of hydrogen knowledge is media coverage, particularly news reports; (3) hydrogen transport applications, especially HFCVs, were more familiar among the public than other use cases; and (4) males above 30 years old appeared the most knowledgeable demographic group.

Additionally, this study reveals more nuanced findings which link hydrogen engagement levels to observed generational gaps. In some situations, hydrogen knowledge is being partially disseminated by the younger generation in active education, whereas for some older members of society, hydrogen awareness may be restricted to vague associations from high school chemistry. When this is the case, there may also be more grounds for scepticism due to historical associations with explosive incidents and subsequent fear of hydrogen [172,175]. Qualitative insights also suggest that households may perceive hydrogen as a less disruptive decarbonisation pathway than heat pumps, nevertheless, consumers are interested to understand more about disruptive impacts. Furthermore, location appears to influence consumer perspectives, with respondents from industrial areas within the vicinity of hydrogen clusters expressing high levels of support for both the twin-track approach and domestic hydrogen futures. By contrast, as proximity from hydrogen hubs decreases, consumers are more conflicted about the transition, especially when living in rural locations, south of London or in South Wales.

The findings of this research can be transferred to other countries considering a similar hydrogen transition pathway to the UK, and frontrunner nations exploring the merits of different hydrogen production pathways (see Section Introduction). Nevertheless, as an explorative qualitative study, this paper is not without limitations and the generalisability of results should be attested to by undertaking national survey studies and cross-country comparative research. Firstly, alternative target groups can be engaged with, such as consumers in more rural parts of the country or with different housing characteristics, thereby helping to inform different aspects of policymaking. Similarly, different approaches could be taken to access richer insights into consumer perspectives of one specific aspect of the hydrogen transition, such as the environmental implications of distinct production pathways. Framings should also extend beyond the parameters of the twin-track approach by including alternative pathways such as nuclear-based hydrogen production where relevant [187].

Such a reframing would call for different information provision materials and may benefit from a more interactive focus group or workshop format, wherein consumer perspectives are gauged in a more longitudinal sense, before and after information exposure. At the same time, a follow-up study in the UK context should verify whether the updated British Energy Security Strategy, specifying at least 50% green hydrogen production for the 2030 target, has influenced consumer attitudes towards the twin-track approach. Moreover, future research should integrate quantitative data collection procedures through large sample surveys to help substantiate the robustness of qualitative insights from this study. Specifically, we advocate for employing partial least squares structural equation modelling (PLS-SEM) [273,274] to explore and validate the antecedents of hydrogen acceptance

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[275,276]. Such contributions would enhance meta-inferences derived from qualitative findings and compensate for the limitation of a small-sample study, which is otherwise constrained to the boundaries of the recruitment process and research design [277].

Moving forward, social scientists should call upon the full repertoire of available research methods, and innovate new research procedures, to better gauge how the difficult choices facing the hydrogen transition may be perceived and received by different consumer segments and the public at large. Additional MMR, employing a multigroup analysis approach, can help ascertain the extent to which specific hydrogen production pathways may garner social acceptance across different consumer segments. Future studies should further investigate whether this support translates into broader approval for the domestic hydrogen transition and willingness to adopt hydrogen homes appliances. For the time being, there remain serious question marks over whether the twin-track approach, as currently understood by the public, will prove compatible with hydrogen acceptance, both at the socio-political and individual level.

Data availability statement

Data underlying this study can be accessed through the Cranfield University Online Research Data (CORD) Repository at:

https://doi.org/10.17862/cranfield.rd.20727982.v1
https://doi.org/10.17862/cranfield.rd.21081670.v1
https://doi.org/10.17862/cranfield.rd.21294873.v1.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.06.297.

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APPENDIX F. Price promises, trust deficits and energy justice: public perceptions of hydrogen homes

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Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Visualisation, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualisation, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Conceptualisation, Writing – review & editing, Supervision.

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Price promises, trust deficits and energy justice: Public perceptions of hydrogen homes

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ABSTRACT

In an era characterised by political instability, economic uncertainty and mounting environmental pressures, hydrogen fuel is being positioned as a critical piece of the global energy security and clean energy agenda. The policy push is noteworthy in the United Kingdom, where the government is targeting industrial decarbonisation via hydrogen, while exploring a potential role for hydrogen-fuelled home appliances. Despite the imperative to secure social acceptance for accelerating the diffusion of low-carbon energy technologies, public perceptions of hydrogen homes remain largely underexplored by the researcher community. In response, this analysis draws on extensive focus group data to understand the multi-dimensional nature of social acceptance in the context of the domestic hydrogen transition. Through an integrated, mixed-methods multigroup analysis, the study demonstrates that socio-political and market acceptance are strongly interlinked, owing to a trust deficit in the government and energy industry, coupled to underlying dissatisfaction with energy markets. At the community level, hydrogen homes are perceived as a potentially positive mechanism for industrial regeneration and local economic development. Households consider short-term disruptive impacts to be tolerable, provided temporary disconnection from the gas grid does not exceed three days. However, to strengthen social acceptance, clearer communication is needed regarding the spatial dynamics and equity implications of the transition. The analysis concludes that existing trust deficits will need to be overcome, which entails fulfilling not only a 'price promise' on the cost of hydrogen appliances, but also enacting a 'price pledge' on energy bills. These deliverables are fundamental to securing social acceptance for hydrogen homes.

1. Introduction

Hydrogen is increasingly considered as a potentially critical industrial feedstock and energy vector [1] for securing a decarbonised global energy future [2,3]. Within recent years, this growing recognition has translated into the launch of national hydrogen strategies [4,5] in over 30 countries [6] spanning much of the globe [7].[1] Additionally, regional hydrogen strategies and action plans have been formulated in countries such as Canada [8,9], Australia [10–12], and the UK [13–15], while roadmaps are also emerging across parts of Africa [16–18]. Considering that Japan was the first country to launch a national hydrogen strategy in December 2017 [19] while the United States formalised its strategy and roadmap in June 2023 [20], it is apparent that the long-held notion of a global 'hydrogen economy' [21–23] is gaining international traction.

The advent of hydrogen economies could prove especially crucial to European countries with large-scale natural gas infrastructure [24], including Germany [25,26], the Netherlands [27,28], and UK [29,30]. Critically, such countries face the dual challenge of mitigating energy security pressures [31–33], while fulfilling climate change commitments [34,35]. The emerging policy push for a low-carbon hydrogen economy is noteworthy in the UK context [36] where the government is supporting a cross-cutting strategy through its 'twin-track' approach, envisioning pathways for both 'blue' and 'green' hydrogen production [29].[2] Despite uncertainties over the feasibility of hydrogen production pathways [37,38], end-use applications [39], and climate change-related impacts [1,40,41], there is a consensus that clean

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[1] Including North America [20,366], Oceania [367,368], much of Europe [25,27,29,369–371], and parts of the Middle East [372,373], Asia [19,374,375] and South America [376,377].

[2] Blue hydrogen relies on steam methane reformation (SMR) with carbon capture and storage (CCS) [378–380], while green hydrogen is produced using water electrolysis sourced from renewable energy sources [381–383].

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Nomenclature

CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
GDNOs	Gas Distribution Network Operators
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air-conditioning
$MtCO_2$	Million tonnes of carbon dioxide
Ofgem	Office of Gas and Electricity Markets
RE	Renewable energy
REMA	Review of Electricity Market Arrangements
SMR	Steam methane reformation
TUC	Trade Union Congress
WTP	Willingness-to-pay

hydrogen technologies can accelerate decarbonisation across 'hard-to-abate' sectors, such as heavy industry [42,43] and heavy-duty transport [44,45].

At present, UK policy makers envision a national hydrogen economy established through synergies between industrial, power, transport, and residential applications [29,39]. This vision [14,29] rests on leveraging the country's natural gas reserves [46,47] and related infrastructure [30,48,49], industrial base [50,51], technological innovation capabilities [52,53], and offshore wind potential [36,53,54] to enable a rapid scaling up of hydrogen energy systems. Although industrial decarbonisation remains the immediate priority [29,39], the UK government is also deliberating the potential role of hydrogen-fuelled appliances for domestic space heating, hot water, and cooking [55], as part of a hybrid decarbonisation strategy [56,57].

While the government is set to take a strategic decision on the role of domestic hydrogen in 2026 [29], the current outlook is somewhat pessimistic following recent local opposition to hydrogen village trials in the North of England [58–61]. In July 2023, consumer resistance culminated in the cancellation of a planned hydrogen trial for Whitby village in Ellesmere Port (Cheshire) [62],[3] which may have been pre-empted by a more comprehensive understanding of social acceptance dynamics. However, due to the nascency of hydrogen home appliances [63,64], the social science research agenda on domestic hydrogen acceptance [65] remains embryonic [66]. Emphatically, Palomo-Vélez et al. [67] underline how a deficit in "public support can grind energy projects to a halt," while impeding the implementation of associated energy policies [67]. Foremost, events in Whitby provide a cautionary tale of what may unfold when social acceptance is insufficiently understood and accounted for. Foreseeably, the cancellation of the Whitby trial has hindered prospects to deploy hydrogen homes, which may impact the wider trajectory of the national hydrogen economy.

Against a volatile socio-political landscape and socio-economic environment [68] in which energy security is a focal point [69–71], this research examines public perceptions of domestic hydrogen [72,73] across dimensions of socio-political, market, community, and household acceptance [74–77]. The underlying objective is to evaluate consumer attitudes towards hydrogen homes by examining acceptance dynamics in relation to critical factors such as public trust, financial perceptions, community benefits, disruptive impacts, and equity implications [73,75]. The study evaluates respective acceptance dimensions to assess which areas may be most at-risk and for which parts of society.

Recognising that the 'human dimension' of technology acceptance [78–80] will shape energy transition pathways [81–84], this study is motivated by the need to bridge a critical knowledge gap on public perceptions of hydrogen homes [73]. Deeper comprehension of this topic may entail important implications for 'hydrogen futures' [85,86] and global decarbonisation pathways [87–90]. The study draws on qualitative data from a series of online focus groups conducted between February and April 2022 to engage with hydrogen perceptions in the UK context. In doing so, this contribution supports the call for empirical analysis on hydrogen acceptance [77,91,92], while engaging with the contested discourse around residential decarbonisation pathways [93,94]. The research design facilitates an integrated, mixed-methods multigroup analysis, whereby several consumer segments compose the sample ($N = 58$), enabling opportunities for comparative assessment across a range of social acceptance metrics.

The rest of the study is structured as follows to fulfil its aim and objectives. Section 2 outlines the macro- and micro-level implications of transitioning to hydrogen homes. Section 3 reviews the literature on socio-political, market, community, and household acceptance of low-carbon energy technologies [74] and hydrogen energy technologies [73,75]. Section 4 describes the methodology, while Section 5 reports key findings on domestic hydrogen acceptance based on the statements of focus groups participants. Section 6 discusses critical insights on different dimensions of domestic hydrogen acceptance. Section 7 concludes the study by highlighting implications for stakeholders and opportunities for future research.

2. Macro- and micro-level implications of hydrogen homes

2.1. Trends in UK carbon emissions and decarbonisation policy

Currently, domestic heating is responsible for approximately 14 % of total UK carbon emissions, whereas cooking contributes to around 2 % [95].[4] Addressing the carbon footprint of the residential sector entails rapidly phasing out 21.2 million gas boilers and 12.7 million gas cookers (hobs and ovens) [96,97] currently installed across 84 % of the housing stock (~23 million properties) [96,98],[5] in addition to decarbonising off-grid properties [72,99]. Countering this imperative, around 1.67 million gas boilers were purchased by UK consumers in 2019 [100].[6] In view of these trends, it is evident that a portfolio of low-carbon energy technologies such as heat pumps, district heating, and possibly hydrogen will be needed to decarbonise the UK housing stock [99,101] in support of net-zero ambitions [102,103].

Supporting the vision for low-carbon heating, a policy ban on gas and oil boilers in newbuild homes is expected to be imposed by 2025 [104]. In parallel, the UK's leading boiler manufacturers are currently developing 'hydrogen-ready' boilers, which are expected to be price competitive with existing gas boilers [105,106]. Specifically, the market price of hydrogen boilers could reach parity with gas boilers before 2030 [107], as supported by a recent 'price promise' made by the boiler industry's 'Big Four' (Worcester Bosch, Vaillant, Baxi, and Ideal) [108].

At the macro-level, the domestic hydrogen transition would involve repurposing the UK's national gas grid to support the transmission and distribution of hydrogen [109–111], as reflected by growing ambitions for developing 'hydrogen backbones' (i.e. large-scale, interconnected pipeline systems) [112,113] and regional hubs around major industrial clusters [114–116]. At the micro-level, transitioning to 'hydrogen homes' [117,118] entails deploying low-carbon boilers and cooking

[3] The cancellation was made effective by Energy Minister, Lord Callanan [59].

[4] Between 2014 and 2018 energy consumption and emissions from domestic space heating increased by 9 % and 8 % Geels [327], followed by a 2 % increase in domestic energy use during the COVID-19 pandemic in 2020 [384].

[5] Around 30 % of the country's housing stock (~8.5 million properties) is classified as 'hard-to-treat' [385], contributing towards around 50 % of household emissions [386].

[6] Representing an estimated 7 % of grid-connected properties [56].

appliances [55] to support the 'deep' decarbonisation of the residential sector [75,119,120].

Although proponents of hydrogen argue that it could provide a relatively non-disruptive and cost-effective pathway for decarbonising homes [121], the techno-economic feasibility of domestic hydrogen is yet to be established [24,122]. Barriers to hydrogen technology deployment such as safety and cost will need to be overcome to support a socially acceptable transition [24]. As articulated by Jones et al. [123], addressing constraints and bottlenecks to technology diffusion calls for "increased collaborative research between social scientists, pure scientists and engineers" [123]. As a social science contribution, this study aligns to the call for integrating consumer acceptance into assessments of technology adoption [77,124], but makes no assumptions about the techno-economic feasibility of deploying hydrogen homes at scale.

2.2. Trends in the energy price cap

Establishing techno-economic feasibility and social acceptability are less probable during times of political and economic instability [125], adding to the challenge of enacting a clean hydrogen economy within a net-zero timeframe [126]. This study coincides with a time of extreme political and economic instability, compounded by the COVID-19 pandemic [71,127],[7] Russia-Ukraine conflict [31,32,128], and a host of 'threat multipliers' [70,129], which have culminated in an unprecedented energy crisis [130], as demonstrated in Fig. 1. During 2021 nearly 30 energy companies went bankrupt in the UK, affecting over four million customers [131,132]. Continuing the previous year's trend, Bristol Energy collapsed at the start of 2022, displacing an additional 176,000 customers [131,132]. Following these developments, the energy price cap (EPC)[8] increased by £139 (~12.2 %) in October 2021, before reaching £1971 in April 2022 [69]. Shortly after, forecasts suggested the next EPC would exceed £3000 [69,130,133], giving rise to concerns that the number of households facing fuel poverty could double from 6.5 to 12 million [69].

In October 2022, the EPC reached £3549; coinciding with the introduction of an energy price guarantee (EPG)[9] of £2500 to help alleviate economic pressures. Thereafter, the EPC peaked at £4279 in January 2023 before falling to £3280 in April 2023, while the EPG remained in place. Reflecting seasonal demand for heating, the latest EPC for July to October 2023 is set at £2,074, while the EPG has been increased to £3000 and will remain in place as a safety net until the end of March 2024. Given recent trends, there are prevailing concerns that previous fuel poverty estimates could further increase by the end of 2023 [134,135].

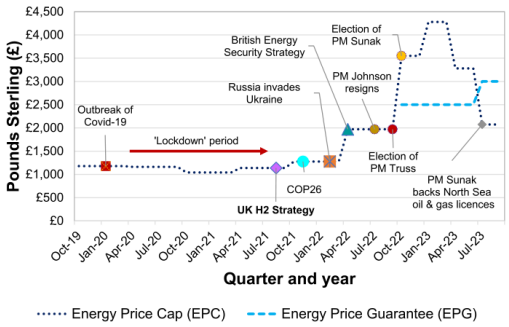

Fig. 1. Overview of political and economic developments affecting UK energy markets.

Unprecedented fluctuations in the EPC over the past 18 months (see Fig. 1) have led to emerging energy security policies, such as ambitions for up to 50 GW of offshore wind capacity by 2030 and 24 GW of new-build civil nuclear generation capacity by 2050 [53], alongside recent plans for hundreds of new North Sea oil and gas licences [136]. Such developments will have notable implications for prospective hydrogen production pathways [29]. Against this background, Section 3 further contextualises the study by reviewing the literature on socio-political, market, community, and household acceptance [73,74,77] for low-carbon and hydrogen energy technologies. As argued throughout the study, the emerging contours of hydrogen acceptance may yield important implications for the trajectory of UK energy policy.

3. Dimensions of social acceptance

Traditionally, international energy studies have engaged with the socio-political, market, and community dimensions of social acceptance [137–139], following "the triangle of social acceptance of renewable energy innovation" proposed by Wüstenhagen et al. [74] in 2007. Notably, the framework was initially developed to better understand community responses to onshore wind projects [74,140], but has since been applied to a wide range of energy technologies [76,123,137] and contexts [141–143].

In a recent contribution, Gordon et al. [75] incorporated additional dimensions of attitudinal and behavioural acceptance when conceptualising a novel multi-dimensional framework for examining domestic hydrogen acceptance. The framework integrates socio-psychological and socio-cultural factors [75], alongside socio-political, economic, and contextual factors embedded within traditional acceptance dimensions [73], thereby elevating the role of consumers in household energy adoption. Following the tenets of the five dimensions framework [75], the next sub-sections engage with social acceptance at the socio-political, market, community, and household level, reflecting the conceptual approach visualised in Fig. 2.

3.1. Socio-political acceptance: public trust in the low-carbon transition

Socio-political acceptance rests on the extent to which consumers view domestic hydrogen appliances as "a legitimate and just technology pathway" for improving society, the economy, and environment [75]. A key component of socio-political acceptance for the low-carbon energy transition is public trust [89,144,145]. While public trust[10] is a nuanced [146] and multi-dimensional concept [147,148], it essentially reflects the degree to which society perceives stakeholders to have public-serving motives [67,149] linked to levels of competence and integrity [145,150,151].

Drawing on recent examples, the government announced a moratorium on fracking in 2019 following local opposition [152], while the nationwide smart meter roll-out continues to face consumer resistance due to public mistrust, which has stifled market uptake [153–155]. Furthermore, it is possible that the cancellation of the Whitby village trail could lead to negative 'spillover' perceptions [156] towards other parts of the hydrogen economy. Reflecting this prognosis, Aditiya and Aziz [157] note the extent to which "low public trust is a potential hindrance" when aiming to introduce sustainable hydrogen

[7] The UK's first two patients tested positive for Coronavirus on January 29th, 2021.

[8] Set twice a year and regulated by the Office for Gas and Electricity Markets (Ofgem) to a limit the unit rate and standing charge that energy suppliers can charge for standard variable tariffs.

[9] A government subsidy introduced to limit the charges per unit of gas or electricity.

[10] We refer exclusively to 'public trust' throughout the study and consider this term to be interchangeable with 'social trust' in the context of this analysis.

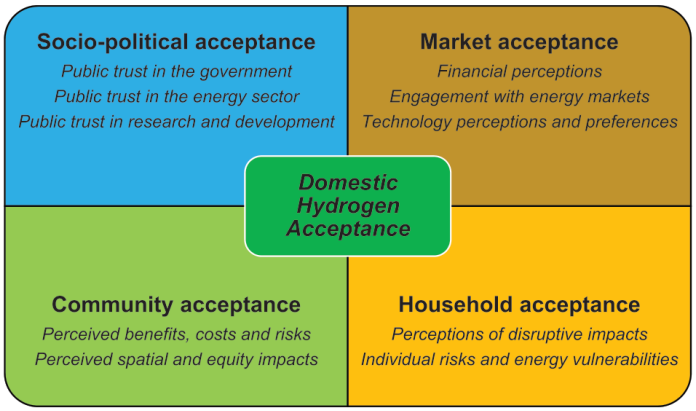

Fig. 2. Conceptual framework for examining domestic hydrogen acceptance.

technologies, while Dwyer and Bidwell [158] emphasise the importance of public trust to scaling up renewable energy (RE) projects. Accordingly, the cancellation of the Whitby village trial may diminish public confidence in hydrogen homes, as well other sectors of the hydrogen economy.

Contrary to renewed policy commitments towards climate change targets [50,102,103], data suggests public trust in net-zero actors including the UK government remains low [159,160]. Public trust in further constrained owing to a lack of confidence in energy suppliers [78,161–163]. In 2020, Ofgem [164] reported that only 35 % of consumers ($N = 4608$) were trusting of energy companies compared to 45 % in 2019, while 28 % expressed distrust.[11] While these trends can be partly attributed to the socio-economic repercussions of COVID-19 [164], mistrust stems primarily from negative public perceptions concerning the profit motives of the energy industry [160,165]. Similarly, in the Dutch context, the intentions of energy suppliers to reduce CO_2 emissions has been met with public scepticism [149]. Moreover, the government is sometimes considered complicit due a lack of regulation and legal enforcement to help curb opaque business practices [166,167].

Recent hydrogen acceptance studies conducted in the UK [163,168] reflect the extant deficit in public trust. Employing a seven-point Likert scale (1 = strongly disagree; 7 = strongly agree) Van Alstine and Bastin [168] found that survey respondents in the North of England ($N = 578$) were doubtful whether the national government ($M = 3.7$), as well as local councils ($M = 4.0$), could be trusted to make competent decisions about hydrogen deployment. Similarly, Sovacool et al. [89] found that only 40.6 % of UK respondents ($N = 2000$) regarded the government as a trustworthy entity, whereas this figure increased to 50.4 % for scientists. Conversely, consumers are typically more trusting of local tradespeople and professionals [89,169,170].

Critically, the public remains sceptical about the commitment of government and industry towards facilitating distributional and procedural justice [73,160] (i.e. a socially just distribution of resources and benefits, and fair and inclusive planning processes). Nevertheless, the public expect these entities to ensure stringent management of health, safety, and environmental issues [163,171]. Supporting this assessment, the study of Van Alstine and Bastin [168] reported stronger levels of public trust in the notion that hydrogen technologies would only be introduced if safe ($M = 5.1$). To derive deeper insights regarding the trust dynamics of the domestic hydrogen transition, Sections 5.1 examines qualitative evidence regarding public trust in the UK government, while Section 5.2 broadens the discussion to perceptions of other key actors and stakeholders, such as energy companies, gas distribution network operators (GDNOs), boiler manufacturers, and research institutes.

3.2. Market acceptance

When purchasing energy-efficient appliances [172], households operate as both investors and consumers [74]. Consequently, market acceptance entails a combination of economic and social factors [75,137] involving financial perceptions, consumer engagement in energy markets, and technology choice and personal preferences, which are reviewed in the following sub-sections.

3.2.1. Financial perceptions

The broader literature on hydrogen energy acceptance [77,91], including studies on hydrogen fuel cell vehicles [173], highlights the importance of economic factors [174] and associated financial perceptions [77,91]. These observations are also consistent with studies on low-carbon energy technologies, which find financial factors to be the most critical barrier to consumer acceptance [175].

Market development for hydrogen homes is contingent on interactions between several key stakeholders across the supply chain and a range of intermediaries [24]. However, prospects for market uptake may ultimately be determined by two key factors: the ability and willingness of consumers to invest in hydrogen appliances [24,73]; and the extent to which potentially higher taxes and energy bills may potentially offset the ability or willingness-to-pay (WTP) for domestic hydrogen [72,78,176].

Independent sources estimate the total costs of the hydrogen conversion to lie between £3000 to £3300 for the average UK home [177,178].[12] These figures suggest that hydrogen home appliances would be cheaper than heat pumps in terms of up-front costs [178–180]. Additionally, it is forecasted that the market price of hydrogen boilers should reach parity with gas boilers before 2030 [107], as supported the industry's recent price promise [108].[13] While uncertainties remain

[11] Trust in the energy sector to treat customers fairly and to charge a fair price was also limited to around 40 %, while around one-quarter of respondents expressed distrust [164].

[12] It is expected that hydrogen appliances and labour will account for around half and one-third of total costs, respectively [177].

[13] Similarly, the price of heat pumps is anticipated to decline as the market develops and economies of scale are achieved domestically [387,388].

regarding cost impacts [24,29,181,182], evidence suggests financial perceptions will prove a critical factor of domestic hydrogen acceptance [73,78,183], especially for households facing economic hardship [176, 184] and fuel poverty [71].

At present, research evaluating financial perceptions for hydrogen home appliances remains scarce [73], with evidence limited to studies in the UK [163,168,176,185], Australia [186–188], and Europe [89,189]. Surveying consumers in five European countries in 2020 (N = 10,109), Sovacool and colleagues [89] reported that 17.6 % of UK respondents (N = 2000) would be willing to pay €20/month more (equivalent to about £200/year) on their bills for low-carbon heating, compared to 46.9 % among Swedish respondents,[14] however the study failed to distinguish between technology types (e.g. biomass boiler, heat pump, district heating).[15] By contrast, a hydrogen-specific study conducted in the same year (2020) within the UK (N = 1027) reported relatively low levels of concern about the switchover leading to a 7 % increase in gas bills [185]. However, it should be stressed that both studies were conducted prior to the current energy crisis, which infers WTP has likely decreased since 2020.

Despite the imperative to quantify and unpack consumer perceptions of cost factors, there remains a lack of concrete evidence on this aspect of the hydrogen transition; beyond the acknowledgement that government subsidies and financial schemes are imperative to realising a low-carbon domestic energy future [168,185]. Although forecasting future hydrogen production costs is subject to significant uncertainty [190] and further compounded during times of political and economic crises [70,191], efforts must be taken to ensure hydrogen acceptance is examined meaningfully by accounting for WTP.

Context-specific analysis on market acceptance, as presented within Sections 5.3 and 5.4 of this study, can help validate whether UK consumers may have a higher WTP for low-carbon products, as suggested by *Ørsted in 2018* [192], Ernst & Young in 2021 [193] and Deloitte in 2022 [194]. More broadly, insights on financial perceptions of domestic hydrogen can enhance research findings on consumer WTP for green technologies and services [195,196], which is a pivotal aspect of forecasting national energy transitions [197].

3.2.2. Consumer engagement with energy markets

Historically, the UK energy market has been dominated by six companies, with British Gas holding the largest market share [198,199]. Five companies[16] have more than 70 % of the total market share, while a newcomer (Octopus Energy) has around 11 % market share [200]. Analysts argue that the profitability of such companies has been consolidated through a 'loyalty penalty', whereby customers loyal to the same supplier remain on expensive default standard variable tariffs [201, 202]. Consequently, around 50 % of households, typically those in fuel poverty or facing conditions of fuel stress, are significantly overcharged for their energy usage [203,204].

Ofgem [205] have surveyed consumer perceptions of the UK energy market over several annual quarters. The most recent surveys have coincided with the ongoing global gas crisis and subsequent changes to the EPC, which continue to impact energy affordability, market stability and consumer engagement [206,207]. Critically, in the third quarter of 2022,[17] it was reported that 53 % of consumers had affordability concerns, compared to 51 % in the first quarter of the year [207]. Moreover, across twelve surveys conducted since the third quarter of 2019, there are persistent trends of decreased satisfaction and increased dissatisfaction among consumers, as depicted in Figs. 3 and 4.

In terms of net satisfaction,[18] the mean peak can be traced to the second quarter of 2020 (M = 77.1 %), while the most recent survey (Q3 2022) has seen a decline of over 12 % (M = 65.0 %), compared to a mean of 73.6 % for the period (SD = 4.1). Mirroring these trends, levels of net dissatisfaction have more than doubled since the third quarter of 2019 (M = 7.4 %), reaching a historic high of 15.0 % three years later.[19] Declines in confidence and satisfaction have proved especially pronounced in relation to ease of contacting energy companies, and comparing energy suppliers and prices.

Overall, data collected by Ofgem [164,204,207] shows that vulnerable consumers remain less engaged, whereas owner occupiers, mid-ages, and higher social grades are more prone to switching energy supplier. Consumers with a propensity towards switching energy suppliers also feel more confident about comparing energy deals and making the best choice. By contrast, disengaged consumers are generally more risk-averse when it comes to switching supplier and more likely to prefer larger or better-known suppliers [164,207]. Moreover, vulnerable consumers such as those with a long-term illness or disability are significantly more likely to be dissatisfied with their energy supplier [206,207], emphasising the need for policy prescriptions to address energy vulnerabilities in the UK [135].

Supporting these findings, studies in both the academic [73,208, 209] and grey literature [185,210] attest to widespread levels of consumer disengagement with energy markets, especially beyond the main activity of switching tariff or supplier. For example, Spence et al. [211] found that consumers in lower social grades and reliant on prepayment meters were less likely to adopt demand-side management technologies, despite facing affordability challenges. Consequently, this study coincides with an unprecedented period of socio-economic hardship and anxiety, which has negatively impacted satisfaction with energy suppliers and markets across a range of metrics, as examined in Section 5.5.

3.2.3. Technology perceptions and preferences

In addition to financial perceptions and engagement with energy markets, technology perceptions and preferences will influence market acceptance for hydrogen appliances [73]. Mirroring the market for energy suppliers, the boiler manufacturing market is highly oligopolistic, with four companies having most of the market share [105,106]. In parallel, this group is leading the charge to develop hydrogen-ready appliances, which continue to be tested in trials and demonstration projects [29,212]. It follows that consumers would be selecting their hydrogen appliances from existing companies such as Worcester Bosch [213,214], unless new companies were to enter the market over time.

Given that the average gas boiler is usually replaced after about 12 years [183,215], domestic hydrogen adoption may be partly driven by brand familiarity [73], as is the case for other consumer durables such as heating, ventilation, and air-conditioning appliances [216]. For example, Seitz et al. [216] found that consumers were willing to spend more on an air-conditioner with a reputation for quality, which was positively associated with an established brand name. Analysing purchasing trends in the Taiwanese refrigerator market, Lin et al. [217] found that the drivers of repeat purchase among consumers were "ease of use, innovative design, design excellence, and extra features,"

[14] Additionally, German, Spanish, and Italian respondents had a significantly higher WTP than participants in the UK.

[15] Notably, hydrogen was reported to be a much less popular option across all countries. Only 11 % of respondents preferred a switch to hydrogen compared to 32 % choosing solar heating [89].

[16] British Gas, E.ON, EDF, ScottishPower and OVO.

[17] Data was collected using a mixed-methods approach, consisting of computer-assisted web-interviewing (N = 3082) and computer-assisted telephone interviewing (N = 150) between July and August 2022. No data was collected during the second quarter of 2022.

[18] Ofgem employed the following five-point Likert scale in their surveys: Very satisfied; Satisfied; Neither satisfied nor dissatisfied; Dissatisfied; Very dissatisfied. A sixth option, 'Unsure' is also included.

[19] Compared to a mean of 9.5 % for the period (SD = 2.5).

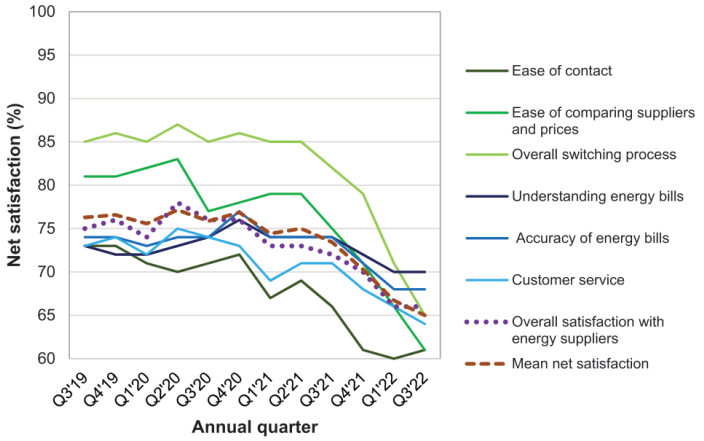

Fig. 3. Net satisfaction with energy supplier and markets. Authors' design based on [206,207].

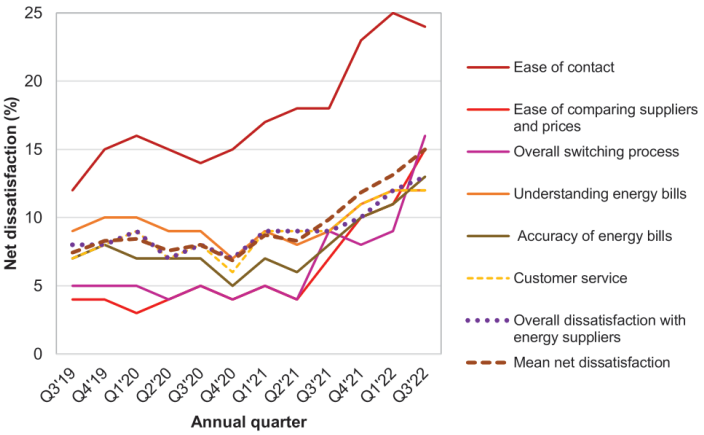

Fig. 4. Net dissatisfaction with energy suppliers and markets. Authors' design based on [206,207].

whereas Bayus [218] highlighted the importance of product performance for brand loyalty towards consumer durable products.[20] Alternatively, in addition to consumer dissatisfaction, limited diversity in terms of models and sizes may trigger brand switching [217].

Energy technology acceptance, particularly for smart homes devices and appliances, is higher when benefits are easily recognisable [219]. However, identifying cost-effective and energy-efficient appliances remains a challenging proposition for most consumers [220]. Additionally, when health and safety issues arise or are otherwise anticipated, consumer acceptance is likely to waver [219]. Concerns around hazards and risks could impede positive perceptions of hydrogen technologies [176,221,222], irrespective of their actual safety performance.

Counteracting these acceptance barriers [24], market reports suggest UK consumers have a growing preference for embracing sustainability [194] and adopting renewable or low-carbon energy products across a wide range of goods and services [192]. It follows that communicating the potential environmental benefits of hydrogen appliances may prove critical to encouraging market uptake and building social acceptance [73,223].[21] Consequently, for some consumers, technology perceptions and preferences will interact with knowledge and awareness of environmental impacts [75]. Accounting for these dynamics, Section 5.6 explores consumer preferences for appliance brands and models in the context of hydrogen homes.

[20] While 'brand equity' can be defined in terms of the "added value with which a given brand endows a product" [389], 'consumer-based brand equity' is composed of brand awareness and image [390] which may promote brand loyalty [216].

[21] However, the emissions intensity of blue hydrogen [391–393] could undermine its role as a transitional fuel [38,394] towards realising a green hydrogen economy [395,396], while green hydrogen is not without its sustainability challenges [397] including GHG emissions risks from leakage [398].

3.3. Community acceptance: spatial dynamics and energy justice

Community acceptance for domestic hydrogen will be influenced primarily by public perceptions of perceived benefits, risks, and costs, which relate to economic, social, and environmental impacts [73,75]. More precisely, community acceptance is configured by perceptions of distributional, procedural, and recognition justice [224,225], which reflect equity impacts at the local level [226,227]. Accordingly, in a recent review, Gordon et al. [73] explored community acceptance in respect to the "spatial dynamics of hydrogen communities" and potential energy justice impacts.

The importance of regional industrial clusters and innovation systems has been identified in the context of hydrogen and fuel cell development across Europe [228]. Madsen and Andersen [228] highlighted the role of geography in establishing hydrogen hubs and engaging stakeholders in the UK Midlands and parts of Wales, finding an association between high activity in fuel cell development and innovativeness. Furthermore, industrial agglomeration around the hydrogen economy has been shown to support synergistic benefits [228] and public trust [229].

The geographical dynamics of the UK hydrogen transition are strongly dictated by activities around large industrial clusters [230], which contribute significantly to national GHG emissions [114,231,232].[22] Within such areas, large-scale facilities for a range of energy-intensive activities such as electricity generation and distribution, oil refining, manufacturing and distribution are co-located [114]. Adopting this terminology, a hydrogen cluster can be defined as follows:

A geographic region where one large or a co-operative of smaller potential demand exists or alternatively as site which is advantaged through access to land and infrastructure such that it has the potential to become a hydrogen hub and distribute hydrogen to outlying customers [233].

To date, two hydrogen clusters have received Track-1 government funding as part of the Carbon Capture, Utilisation and Storage (CCUS) Cluster Sequencing Process [234]. The HyNet industrial cluster covering Merseyside and North Wales [235], and the East Coast Cluster linking Teesside and the Humber [115] received approval, while the Scottish Cluster (Projects Acorn Hydrogen and Fife Hydrogen Hub) was announced as a reserve [236].[23] Consequently, the emerging spatial dynamics [237] of the domestic hydrogen transition revolve around coupling heat decarbonisation to industrial strategy [29,51,101].

Given that 23 million UK households rely on natural gas for heating [110], while around four million remain unconnected to the gas grid [238], the transition to hydrogen homes would entail a significant degree of spatial exclusivity [73,75]. Many parts of the country, both grid-connected and off-grid, are strongly characterised by "uneven economic and social geographies" [176], which poses an imminent risk to proliferating fuel poverty [71,135]. There is an imminent risk of exacerbating energy inequities should off-grid properties lag in the decarbonisation timeline [72,99]. These disparities could compound the difficulty of securing a socially acceptable and efficient decarbonisation pathway [75], aligned to the principles of energy justice and a 'just transition' [239–242].

Motivated by a similar rationale, Upham et al. [243] recently developed an integrated framework engaging with justice issues linked to industrial decarbonisation, wherein community-based planning and community capacity enhancement are important aspects of social acceptance. Furthermore, Devine-Wright [114] has explored the relationship between reinhabiting industrial sites and community acceptance, reflecting the need to understand interactions between siting decisions and public engagement. Interestingly, Cowell [237] found many UK gas projects have successfully reinhabited sites of former fossil fuel power stations, whereby developers mobilised arguments around the net environmental benefits of such projects, while encountering minimal local resistance about landscape impacts.

At present, UK studies suggest mixed perspectives regarding the community impacts of domestic hydrogen [65,78,168]. Van Alstine and Bastin [168] reported moderate to high levels of local acceptance for hydrogen stimulating a green economy in Leeds, but also noted high levels of uncertainty as to whether hydrogen technologies would benefit local communities, as opposed to large businesses ($M = 3.4$).[24] Relatedly, Scott and Powells [65] noted strong concerns over socio-economic risks and distributional injustice among survey respondents in the North of England, while focus group respondents from Manchester and Birmingham expressed reservations over exacerbating energy vulnerabilities [78], which has also been echoed in the Australian context [72].

Given the potential synergies between industrial and residential sectors in the context of the UK hydrogen transition (see Section 1), community acceptance should be examined in relation to place-specific dynamics [75,114,244]. While some initial insights on community acceptance have been generated, few follow-up studies have been conducted to validate pre-COVID 19 results. Moreover, there is limited evidence regarding the equity aspects of the hydrogen switchover [72,78,176]. Similarly, efforts to explore the spatial dynamics [245–247] and justice implications [224,248,249] of the energy transition continue to lag [75]. To help reverse this trend, Sections 5.7 and 5.8 engage with community acceptance through the lens of perceived benefits, costs and risks, in addition to spatial dynamics and energy justice.

3.4. Household acceptance: temporary disconnection from the gas grid

Should the domestic hydrogen transition receive policy support in the upcoming years [29], the switchover process would require households to be temporarily disconnected from the gas grid while appliances are changed or upgraded [250]. Disruption levels will depend on the duration of disconnection, which may range from several hours to a few days [78,162,185].

A nationally representative UK survey ($N = 2000$) conducted by the Decarbonised Gas Alliance [162] provides the only available quantitative evidence on this aspect, finding 39 % of respondents were 'unconcerned' about being without gas 'for a few days in summer' compared to 34 % expressing 'concern'. Additionally, the researchers [162] conducted four focus groups ($N = 32$) split between the North of England and Greater London, which suggested concerns over short-term disruption could be mitigated and appeased in most cases. While the prospect of disconnection raised some initial concerns, respondents were broadly satisfied provided solutions such as meal vouchers, bottled gas or financial compensation could be offered [162].

In a study conducted with four focus groups ($N = 39$), representing consumers from different housing segments in Manchester and Birmingham, Grey et al. [78] specified a hypothetical scenario in which 300 homes would be switched to hydrogen in the summer over a three-to-four-day period. Notably, participants emphasised that heating and hot water would still be needed during the summer, while questioning the feasibilty of completing the switchover in less than four days

[22] It is estimated that the industrial sector is responsible for approximately 16 % of total UK CO_2 emissions [399], with the country's six largest industrial clusters (Humberside, South Wales, Grangemouth, Teesside, Merseyside, and Southampton) contributing around two-thirds of national industrial emissions [232]. Additionally, the Thames Estuary region emits around 12 million tonnes of carbon dioxide equivalent per year ($MtCO_2$/year), which is almost on par with Humberside (~12.4 $MtCO_2$/year) [232].

[23] In 2020, the Thames Estuary Growth Board also launched its 'Green Blue' action plan [400] and 'hydrogen route map' to accelerate its decarbonisation agenda for industry and transport, both on land and water [233]. The 2022 Capital Hydrogen programme also comprises a series of projects for the London and Southeast region over the next 15–20 years [401].

[24] As measured on a seven-point Likert scale (7 = Strongly agree).

[78]. Other complaints were voiced over the disruption to home workers, alongside broader impacts to living arrangement during the switchover period [78]. Conversely, when conducting deliberative workshops, Fylan et al. [185] reported an underlying assumption that UK respondents expected the disconnection period to last a few hours, which resulted in minimal qualitative evidence on tolerance limits.

Across the few studies conducted in the UK, one consistent finding in the need to safeguard vulnerable parts of society during the switchover period [78,162,185], which is a concurrent theme in Australian research [72]. However, in addition to the lack of both quantitative and qualitative evidence on perceptions regarding temporary disconnection, the referenced studies date back to 2019–20. In response, Section 5.9 contributes up-to-date and in-depth findings on this dimension of household acceptance, which may help steer strategic decisions regarding the acceptable duration of the switchover process, while accounting for perceptions of individual risks and associated energy vulnerabilities.

4. Methodology

4.1. Focus group design and sample characteristics

This research involved carrying out 10 semi-structed online focus groups between February and April 2022 using the Zoom platform [251]. Based on prior research on early adoption [252,253], environmental engagement [254–256], low-carbon developments in industrial areas [115,234,235], and fuel poverty impacts [257–259], participants were purposively selected to represent a range of different consumer segments, as described in Fig. 5. In addition to enabling opportunities for comparative analysis, this approach was implemented to account for the potential impact of citizens interested in community renewable energy (FG1, $N = 5$; FG2, $N = 6$), consumers with a propensity to be early adopters (FG3, $N = 3$; FG9, $N = 8$), residents engaged in environmental issues (FG4, $N = 3$ and FG8, $N = 9$), people living in industrial towns (FG5, $N = 5$), households facing fuel poverty pressures (FG6, $N = 3$ and FG10, $N = 10$), as well as a 'baseline group' (FG7, $N = 6$) which excluded these variables.

Three modes of recruitment were employed by the research team to secure participants for the focus groups: networking[25] with members of the local community in Marston Moretaine, Bedfordshire (FG1 and FG2); employing a market research company (FG3, FG4, FG5, FG6 and FG7); and through outreach on social media platforms (FG8, FG9 and FG10). To support the recruitment process, five Qualtrics surveys were designed with a series of specific filters matching these requirements, in addition to context-specific filters described in Ref. [260], and various

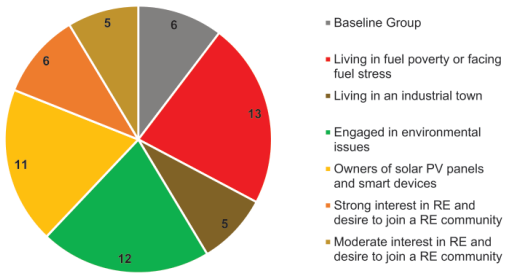

Fig. 5. Distribution of consumer sub-groups.

[25] With the Commercial Director of the Marston Vale Millennium Country Park, members of the Parish Council and local online groups.

quotas on socio-demographic variables (see Supplementary Note 1). While the final sample ($N = 58$) represented several parts of the UK population, some locations such as Wales, Scotland, and the Northeast England were underrepresented (see Fig. 6), which should be addressed in subsequent studies. Overall, this study encountered certain limitations[26] in retrieving a fully nationally representative sample, which is an inherent constraint when adopting the focus groups method [135]. However, by including several sub-groups, the research design helped neutralise a partial lack of representativeness, while supporting the underlying objective to ensure diversity among participants and scope for representing multiple perspectives.

4.2. Focus group format and information provision materials

Based on literature review findings [24,73,75], the research team established a topic guide to motivate discussion on aspects of socio-political, market, community, and household acceptance. Each focus group lasted around 90 min and was moderated by the lead author, with support from co-authors and research colleagues. The same approach and design were maintained throughout each session, supporting consistency in terms of data collection to optimise opportunities for subsequent comparative analysis. In some focus groups, the moderator probed participants with follow-up questions to help extract more nuanced details on their perspectives, while at other times participants required minimal prompting and led the discussion in the first half of the focus group engaged with consumer preferences for cooking and heating technologies as reported in Ref. [260], perspectives on climate change, energy and environmental issues as documented in Ref. [261], and attitudes towards the UK Hydrogen Strategy and production pathways which are examined in Ref. [262]. The second half of the discussion focused on the themes tackled within this analysis, following questions reported in Table 1. To support the discussion, a combination of information provision materials were employed, including two short videos and animated PowerPoint slides (see Figs. 7 and 8).

Leading into the discussion on public trust, participants viewed a Channel 5 News video segment[27] aired on August 17, 2021 to mark the release of the UK Hydrogen Strategy [29]. Following discussion of the video, which included a mix of government, industry, and scientific perspectives on hydrogen, the moderator shared a clip from Northern Gas Networks on the H21 Project [263].[28] This segment provided participants with a visual representation of hydrogen home appliances, as transmitted via the HyStreet demonstration site located at Spadeadam, Northumberland [264]. The video content was restricted to a series of short subtitles, which minimised the potential for bias or emotional cues (see Supplementary Note 2).

Next, the moderator shared an animated PowerPoint slide illustrating the key actors and stakeholders within the UK hydrogen landscape. The slide firstly showed a group of houses and energy companies to illustrate how a given street may have multiple energy suppliers. Next, Fig. 7 presented the four GDNOs responsible for managing the UK grid. Thereafter, interactions between government, industry, and the independent regulator (i.e. Ofgem) were outlined, before highlighting the links between academia and business consortiums, and finally the role of leading boiler manufacturers within the Energy & Utilities Alliance (EUA). Subsequently, participants reflected on their trust levels in different actors and stakeholders, and were prompted to justify their

[26] The sample was broadly nationally representative in terms of gender (slight over-representation of males); loosely nationally representative of housing type and marginally representative of housing type; over-represented by 26–35-year-olds and under–represented by 65+; and had a somewhat higher average number of occupants per household (3.1) compared to the national average (2.4).

[27] https://www.youtube.com/watch?v=g-VpyglBhrI.

[28] https://www.youtube.com/watch?v=CtAzCv5Sc48.

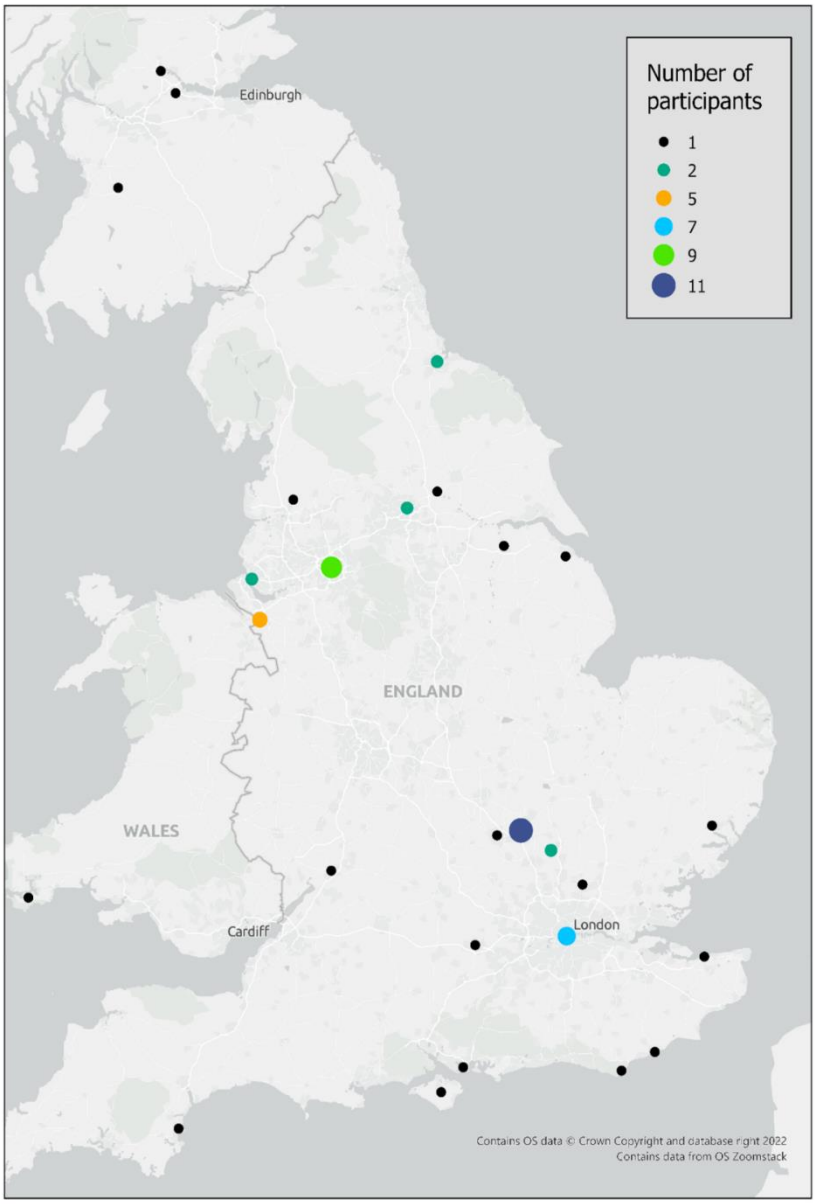

Fig. 6. Location of focus group participants. This map is also included in Supplementary materials by the authors in Ref. [260].

views.

Finally, to help frame the discussion on community acceptance, participants viewed an animated PowerPoint slide illustrating the spatial dynamics of the UK hydrogen transition. The materials informed participants about the location of past and ongoing hydrogen trials and demonstration projects (black dots), the first cities and towns forecasted as potential candidates for deploying hydrogen homes (white dots), and the location of the HyNet and East Coast Cluster projects (red stars). Participants were also provided with additional information about the role of GDNOs and informed about hydrogen activities in Fife, east-central Scotland [265,266].

Table 1
Overview of acceptance dimensions, themes and questions.

Acceptance dimension	Themes	Questions
Socio-political	Trust levels in key actors and stakeholders of the UK hydrogen transition	• How do you feel about trusting the main actors and stakeholders of the hydrogen transition? • How do you feel about having a choice when it comes to switching to hydrogen?
Market acceptance (1)	Choices and decisions regarding energy suppliers, appliance brands and models	• Has anyone changed their energy supplier in the last few years or more recently? • How would you go about choosing your energy supplier if using hydrogen? • How do you feel about having a choice about appliance brand and model?
Market acceptance (2)	Financial perceptions of the purchasing, running and maintenance of domestic cooking and heating technologies	• How do you think the cost of hydrogen appliances should compare to natural gas appliances? • How do you think energy bills for hydrogen should compare to natural gas? • What cost impacts do you expect when it comes to maintenance of your appliances?
Community acceptance	Community benefits, costs and risks of the hydrogen switchover	• What do you see as the potential benefits of hydrogen for your local community? • What do you see as the potential costs or risks of hydrogen for your local community? • How do you feel about having a choice when it comes to switching to hydrogen?
Household acceptance	The disruptive impacts of hydrogen homes and energy vulnerabilities	• How long would you tolerate being temporarily disconnected from the gas grid during the switchiver? • How do you feel about engineers and technicians having access to your home during the switchover?

4.3. Integrated mixed-methods multigroup analysis

In comparison to strictly qualitative or quantitative analysis [267–269], mixed-methods research offers a more complete approach for engaging with complex societal issues [270]. Traditionally, mixed-methods research is conducted via separate qualitative and quantitative stages prior to integration [269,271], however, a convergent method (i.e. bidirectional approach) [272] can also be achieved within a single stage of data collection to merge both 'strands' of evidence more directly [270]. Through this approach, integrated mixed-methods analysis [273] can support 'narrative weaving' [269,274]; whereby qualitative and quantitative results are merged thematically [271] to enhance the scope of findings [273].

Focus groups provide a powerful research method for conducting qualitative social science research [270,275], with strong applicability for examining public acceptance of emerging energy technologies [276,277] and attitudes toward the energy transition [278,279]. Notably, Sandri et al. [72] and Smith et al. [256] also employed focus groups to extract insights on different aspects of hydrogen acceptance. Principally, the focus group format supports flexibility and openness [276], which may reveal important insights otherwise overlooked in quantitative studies. Consequently, the method is recommended for generating deep insights [280,281] on novel topics [276] such as hydrogen homes [262]. However, the risk of potential bias due to the role of the moderator [282] and nature of group-specific dynamics [283] should be recognised, while the online format entails the limitation of digital exclusion [284].

By pooling multiple perspectives and facilitating dynamic group interactions [281,285,286], focus group data can also support a multigroup analysis [287,288], whereby areas of convergence and divergence between participants are thoroughly examined [260,289,290]. While multigroup analysis is usually reserved for analysing large-sample survey data [291–293], this study demonstrates the efficacy of adopting the approach when extracting quantitative insights from qualitative data [294]; equating to an integrated mixed-methods, multigroup analysis, which reflects the end goal in Fig. 9.

Aligning with other studies on energy acceptance [295,296] including hydrogen homes [72], the audio recordings were transcribed and inductively coded for each focus group using NVivo 12 qualitative data analysis software [297]. This approach facilitated an inclusive assessment of all available codes within the dataset [298,299] to support a rigorous combination of thematic and content analysis [300]. Firstly, thematic analysis [301] was undertaken by ordering and analysing consumer responses [302] to help capture the emerging narrative on hydrogen acceptance [72,303]. Secondly, analysing the themes and quantifying these outputs revealed areas of convergence and divergence [302] to enable an inductively-driven, comparative analysis [304–306]. To support narrative weaving throughout Section 5, a combination of illustrative statements and summary tables are provided to reflect the main themes and critical points [135,307].

5. Acceptance dynamics of the domestic hydrogen transition

5.1. Public trust in the government

Trust levels in the UK government varied notably between certain focus groups, revealing a tendency towards scepticism and mistrust in many cases (see Supplementary Note 3). For example, one participant was pessimistic about the future: "*I'm not sure I trust this government a lot to take things forward for the next 10 to 15 years. Will this just be another flash in the pan? I need to see action behind the talk from the government and serious investment*" (FG2:1). In some cases, respondents positioned the government as potentially more trustworthy than other entities: "*I'd hope that the government would be impartial, whereas British Gas or other private companies would obviously have shareholders. I would hope the government would at least want to do the right thing*" (FG7:2). However, other respondents countered this viewpoint: "*the government needs to work on building trust. I would trust the energy companies more than the government*" (FG10:8). By contrast, a minority of participants expressed complete trust in the government and industry, "*the companies, the suppliers and the government, we have 100 % trust and will go with them, especially because it's good for the environment, the future and the earth*" (FG9:10).

In total, one-third of respondents ($N = 19$) discussed trust in the central government, wherein low trust ($N = 10$) prevailed as the most frequent perception, followed by high trust ($N = 6$), and partial trust ($N = 3$). While findings at the sample level serve to emphasise a tendency towards mistrust, it is also noteworthy that specific sub-groups demonstrated clear response patterns, as reflected in Fig. 10. At the positive end of the trust spectrum, owners of solar PV panels and smart devices (FG3 and FG9) expressed unequivocal confidence in the government. By contrast, participants interested in joining a RE community (FG2) or actively engaged in environmental issues (FG4 and FG8) framed their lack of trust around past negative experiences with UK energy policies. For example, one respondent referenced the high cost of heat pumps, problems with solar feed-in tariffs, lack of electric vehicle infrastructure and "*getting stung by diesel cars in 2009*" (FG2:3).

It may be inferred that acquiring solar PV panels and smart devices

Fig. 7. Animated PowerPoint slide depicting key actors and stakeholders within the UK hydrogen landscape. The image is considered a selective representation accounting for active parties as of February 2022, as opposed to an exhaustive representation of the UK hydrogen landscape.

Fig. 8. Animated PowerPoint slide illustrating the spatial dynamics of the UK domestic hydrogen transition. Scotland was partially cut off in the animated slide to enable a clear resolution. The original version of the central map is presented in Ref. [75] where Scotland is fully visible.

instils a stronger sense of confidence in energy policies, which may motivate similar investments. By contrast, aspirations for joining a RE community link to the desire for energy independence, which may be associated with mistrust in the government. Interestingly, baseline respondents (FG7) were equally split between trust categories, while fuel poor/fuel stressed participants (FG6 and FG10) were slightly skewed towards the negative end of the spectrum, which likely reflects their disillusionment with recent government policies.

5.2. Public trust in key actors and stakeholders

In some instances, participants drew more explicit comparisons to other key actors and stakeholders in conveying their trust levels (see Supplementary Note 4). Consistent with international research [153, 188], strong concerns over the profit motives of energy companies and other private organisations surfaced in multiple focus groups (i.e. FG2, FG3, FG4, FG7, FG8). For example, one respondent drew wide approval from other participants when critiquing corporate taxation rates and the profit margins of a major oil producer, "*the government needs to tax it*

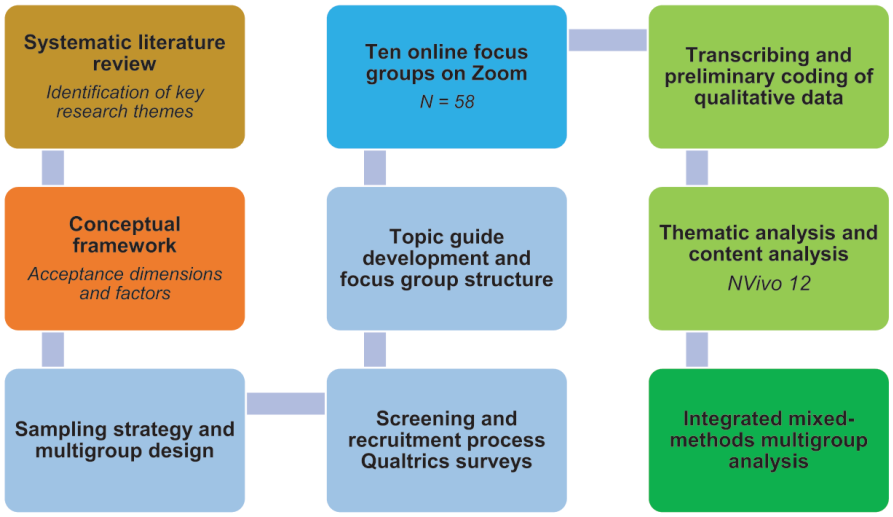

Fig. 9. Methodological approach and research stages.

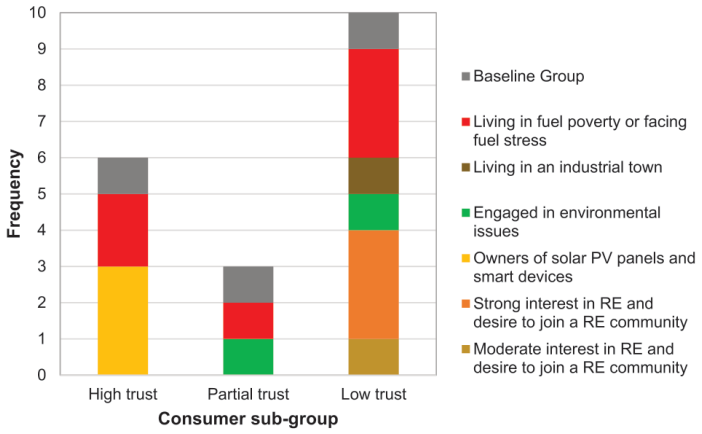

Fig. 10. Public trust levels in the UK government.

because all our gas bills have just doubled, yet BP has just announced £9 billion profit … how about they make £1 billion profit, and our bills stay the same as they were" (FG2:3). By contrast, participants saw Ofgem as a trustworthy entity and were generally confident in information provided by universities and research organisations, which has been found in other studies [163,308].

One respondent (FG8:3) with extensive experience working in community-led housing in the Northeast of England expounded on the "*root of trust*" concerning the UK hydrogen transition:

> "*… well, where is the power? With the people? No! We are being guided by having to put our trust in industry and government and the institutions to come up with the right solutions for the right reasons. Going back to the root of trust and that landscape … we would generally think that the academic institutions would be the most objective and reliable, and I think they are. I'm not disputing it*" (FG8:3).

When public trust wavers, social friction towards the hydrogen economy is more likely [157], which may counteract socio-political acceptance [309] for residential decarbonisation [310].

In some cases, participants also took a macro-view of the UK hydrogen landscape as presented to them in Fig. 7, which drew largely polarising perspectives, as described in Table 2. Most respondents were reassured by the range of actors, while others perceived multiple actor-networks as a potential barrier to implementing meaningful and coordinated action. Notably, a business manager working in the finance sector (FG1:1) viewed the evolving direction of the hydrogen landscape positively, owing to more inclusiveness and stakeholder engagement, reflecting a potential shift towards increased procedural and

Table 2
Perceptions of the macro-environment and emerging hydrogen landscape.

Participant	Illustrative statements
FG1:1	• *At the minute, people investing in ethical and sustainably sourced economics is becoming more and more of a thing, so it's going to get more and more backing as more people are investing into it. It won't just be down to the big wigs in Parliament and the mass stakeholders anymore. It is becoming more sociable and more conscious of society to invest in these areas rather than just the big corporations that are guaranteed to make money. So, it's going to become bigger, and I think not just bigger, but more secure for people going into it because it is getting more backing from Joe Bloggs.*
FG1:5	• *It's very good to see there are brands you recognise and also that there are so many stakeholders involved.*
FG3:3	• *Well, I guess there's a lot of people involved which could complicate things. That could be a problem (FG3:1 responds "Yes")*
FG7:4	• *One problem with the set-up here as portrayed is there is a myriad of organisations involved and that seems to be a recipe for doing nothing!*
FG8:2	• *There are simply too many parties involved for us to understand all this. I used to work for Transco who have now been swallowed up. It's a minefield because you can't actually change the choice of the person who provides your gas piping. You can only change your energy provider in name and label. It's not really changing your supplier.*
FG9:1	• *I think there's quite a large blend of experts, whether it's from companies or manufacturers, government, or utility companies. It seems quite a varied mix which makes me feel better. It's not all coming from the government, or it's not all coming from companies with vested interests.*
FG9:2	• *Now, those organisations … have significant responsibility, legally as well as ethically, and for that reason they have experts … to ensure that things like the [lack of] smell and the concerns that were raised earlier get addressed. So, it's a natural progression and I have 100 % confidence that it can be done safely and ethically.*

distributional justice. However, other respondents cited concerns over potential conflict and inaction among "*a myriad of organisations*" (FG7:4).

Interestingly, there were also objections to privatisation, with one respondent commenting that "*nationalisation is also a good way to go to help the people*," (FG8:7), while another participant elaborated further:

> "*I feel the energy system should be controlled and organised by the government, with the government having total control over it and other stakeholders having just a minimal role in the discussion and actions regarding the energy system*" (FG9:6).

Such perspectives are timely, following a call from the Trade Union Congress (TUC)[29] for government reforms to make the "Big Five" energy companies publicly owned [200,201]. The TUC advocates for a 'social pricing structure' to enable affordable prices for basic energy services, in line with other European countries [200]. Speaking to this issue, one respondent came to the following conclusion: "*the government should not allow the costs to be passed on to the consumer. We all have to play our part [in net zero], but none of us can afford to if it's all on our shoulders*" (FG2:3).

The TUC also cites the past transition from town gas to natural gas [119,311] as an exemplar of the need for coordinated central planning, when it comes to enacting a successful, large-scale domestic energy transition [200]. Reflecting these pressures, the UK government launched the Review of Electricity Market Arrangements (REMA) between July and October 2022 [312]. The consultation aimed to "identify reforms needed to transition to a decarbonised, cost effective and secure electricity system" [313], which may include decoupling electricity markets from the gas price [314]. These ongoing developments reflect the extent to which public trust in both the government and industry will shape the emerging contours of the hydrogen transition, alongside wider prospects for reaching net zero.

[29] A federation of 48 trade unions representing 5.5 million workers [201].

5.3. Perceptions of purchasing costs

Purchasing a new gas boiler is a highly context-specific decision which is often triggered by system breakdown, or usually delayed until the appliance reaches the end of its lifespan (i.e. 12–15 years), especially for low-income earners [183]. Absent of environmental pressures and forthcoming regulations, it follows that a large proportion of the UK housing stock could feasibly continue using their current boiler into the mid-2030s. Having recently replaced their faulty boiler, a solar PV owner reflected this reality: "*The whole question of purchasing costs depends on whether the appliance needs replacing or not … if you have a brand new natural gas boiler, you are not going to want to spend a penny*" (FG9:2).

Relatedly, it was stressed how the lifetime of hydrogen appliances should be "*at least 10 to 15 years, to match the reliability of current gas boilers*" (FG3:1). Having moved to a new build house where the boiler "*is probably the most recent spec*," one participant further explained how an incentive would be needed, otherwise the changeover "*wouldn't be very cost-effective*" (FG5:2). Across the sample, several participants cited the need for subsidies, incentives, or other government schemes to motivate and facilitate the purchase of hydrogen appliances, as reported in Table 3. Furthermore, one respondent linked the domestic hydrogen transition to intergenerational justice [315,316] by drawing parallels between decarbonisation and the public health, "*it's like health, the government need to heavily subsidise this now, otherwise our kids and their kids will be paying for it*" (FG2:3).

Ultimately, it was admitted that "*until you know the economics of it and how much you are going to save, it's hard to say … economically it's unclear, we can't say*" (FG7:1). Additionally, uncertainties in weighing up cost and performance factors were underlined, which could stifle decision-making and consumer uptake if addressed inadequately:

> "*I don't know … if there may be a price hike like when they brought in electric cars like Tesla … it depends about cost-benefit analysis doesn't it? If you are going to pay more and get high quality longevity, then maybe yes. But if there are no sort of guarantees on that, then maybe no. There are a lot of things to weigh up*" (FG4:1).

In addition to referencing the price of electric cars and the capital costs of solar panels, several participants framed their response in relation to the current costs of heat pumps and the Boiler Upgrade Scheme [317], which they saw as too high and insufficient, respectively.[30] However, only two participants (both solar PV owners), shared

Table 3
Consumer perceptions of government support for domestic hydrogen adoption.

Participant	Illustrative statements
FG3:2	• *If they [hydrogen appliances] are a lot more expensive, then people will probably not want them. I can understand they won't be cheap because they are new and because of research and development costs. Maybe there could be something like a green tax benefit for helping the environment in that way.*
FG7:1	• *If you're going to have to spend £6000 to get a new hydrogen boiler, or you have to pay for at least half of it and the rest is a subsidy, then it's not very beneficial to the people that have recently invested in a new gas boiler. I assume there will be some kind of grant in place, so if you've got a ten-to-fifteen-year-old boiler, then it would make sense for you it to change it, and have the government pay towards … they have to assist you.*
FG7:3	• *Decisions will depend on government subsidies which tell you do this please and they dangle the carrot.*
FG9:3	• *An attractive market introductory price would be good … and a long-term deal with potential discount for referrals made to other customers.*

[30] The Boiler Upgrade Scheme supports households with grants of £5000 or £6000 when switching to an air source heat pump (ASHP) or ground source heat pump (GSHP) [101].

a specific figure regarding their willingness to invest in a hydrogen boiler. Estimates ranged from £3000 (FG9:7) to £5000 (FG9:6) for both purchase and installation. A Scottish participant from a family of engineers lent a more technical perspective, "*I'm not sure that it should cost anymore because it might just be the same sort of structure and design. The technology behind that should be much the same*" (FG5:5). Moreover, one participant expressed a position that may represent much of the society, beyond just the North of England or equivalent socio-economic geographies [176]:

> "*I would like the price to stay the same, as I'm not in a position to afford a higher price and I feel this reflects a lot of the UK. If I had the extra money, I would be open to pay more for hydrogen but again there are always other things that you could use your spare cash on*" (FG10:4).

Broadly, respondents communicated three perspectives regarding purchasing costs, which are represented in Fig. 11 (see Supplementary Note 5). The mid-range perspective anticipated hydrogen appliances to be roughly on par with natural gas appliances, or at most, marginally more expensive, while subsidies and incentives like tax benefits should still be in place. Other respondents argued in favour of cheaper appliances to counteract widespread unwillingness or inability to pay and subsequent social resistance. Additionally, several participants anticipated or otherwise accepted that hydrogen appliances will cost more because the technology is new; noting that some people would be willing to pay for environmental benefits, while others would require financial support. Bridging these perspectives, one respondent forecasted potential implications:

> "*If it was the same cost then people wouldn't bother with disruption … if it was cheaper than natural gas, then there would be a more positive uptake. But if it was the same price or higher, nobody in their right mind would agree … and there wouldn't be that public adoption*" (FG9:2).

In total, one-third of respondents ($N = 20$)[31] provided reflections on the purchasing costs of hydrogen appliances, with 'cost parity' prevailing as the most frequent response ($N = 10$), followed by 'higher costs' ($N = 7$), while a minority of participants argued that 'lower costs' is a prerequisite of market acceptance ($N = 4$). However, insistence upon lower costs failed to be communicated by fuel stressed respondents, who instead were split between an expectation for cost parity ($N = 3$) and higher costs ($N = 3$). While limited to a small sample size, this pattern draws attention to a potential lack of confidence for tackling fuel poverty through the deployment of hydrogen homes, which is somewhat unsurprising given recent trends in energy markets. In parallel, there are indications that consumers anticipate cost equivalence, which resonates with the recent price promise from boiler manufactures.

5.4. Perceptions of running costs

Although initially asked about purchasing costs, several respondents contextualised their answer by citing running costs. For example, one participant desired "*to know what the impacts of the purchase will be on running costs … is there any payback there*?" (FG5:3). Other participants (FG9:2, FG9:3, FG10:2) shared this feeling and believed reduced energy bills would help justify the purchase a hydrogen appliance. Commenting on the initial stages of the transition and the prospect of early adoption across the North of England, one respondent conveyed a mix of realism and pessimism:

> "*If it's going to be more expensive … that's not going to go down well without a proper sort of subsidy from the government. It has to be cheaper or on par, but I can't see that happening. I can't see energy costs going down from where they are at the moment*" (FG9:1).

This statement motivated a follow-up reply arguing against a levy on energy bills and potential grounds for aggravating inequities:

> "*I think it's a matter for government and taxation. It shouldn't be a levy on energy bills because that would disproportionately disadvantage those that have a very high energy usage as well as businesses, more so than those that have a really low usage. So, it would have to come from general taxation*" (FG9:2).

Responding to the hope that "*energy bills would be less*" (FG1:3), another respondent stressed the importance of transparency regarding the carbon footprint and environmental impact of hydrogen appliances:

> "*… or at the very least, your energy bills would be equal to now. I would be willing to pay the same if it was a green option, but I would need to know that it really is a greener option and that there isn't any hidden CO_2 in the background*" (FG1:1).

Participants grappling with fuel poverty touched upon similar themes, for example, "*I'm all for saving the environment, but at what cost is it going to come for the normal household*?" (FG6:1), and "*… we all want to do our part to help the environment but being green is very expensive … you want to help the planet to thrive but not at a cost of reducing what we already have*" (FG6:2). Furthermore, their fellow participant elaborated how "*everyone's circumstances are different, income and household wise*" and felt that "*paying for the appliance and having to maybe pay higher energy bills initially would be a bit off putting*" (FG6:3). This viewpoint was further verified in reflection of the financial challenges facing younger age groups:

> "*I have a 22-year-old son moving out soon and it worries me about how he can start off on the property ladder, if you're trying to pay your bills and your mortgage and you have extra costs for the government's net-zero vision. That worries me a lot. I've already seen my energy bills shoot up*" (FG2:1)

Underlining the far-reaching implications of personal circumstances, a Union representative, tasked with helping people with low incomes to pay their energy bills, communicated the plight of citizens in fuel poverty via the chat box:

> "*When the decision really is freeze or starve, there is no money for conversion or for swapping energy supplier, and this is pre- the recent hike … when you have no disposable income at all, the cost to the bank balance overrides all else. In fact, the thought that a change would be mandatory at some point will be one full of anxiety*" (FG8:7).

Overall, most participants expected that running costs would either stay the same or decrease slightly , while several respondents proved unwilling to pay for higher energy bills. However, a minority of respondents had a higher WTP in return for a greener option, underscoring the interactions between market acceptance and environmental perceptions [256,262].

5.5. Perceptions of energy suppliers

To better gauge their experience with and attitudes towards energy companies, participants were asked to confirm if they had previously changed supplier, and to share any relevant details regarding this decision and the process. The rationale for introducing this topic was to ascertain how consumers would feel about potentially changing to a hydrogen-specific provider in the future, and to invite reflections on recent events in UK energy markets. Previously, it has been shown that "widespread consumer disengagement in the energy market remains an obstacle to net-zero ambitions and climate change targets" [73].

Government reports show that a high proportion of UK consumers remain disengaged with energy markets [184], especially in terms of switching energy supplier and tariff [203]. Contradicting the national data, all focus groups proved familiar with recent developments in the UK energy market, and several participants had direct experience of switching energy provider. In most cases, respondents had elected to

[31] One respondent provided a dual perspective (FG5:5).

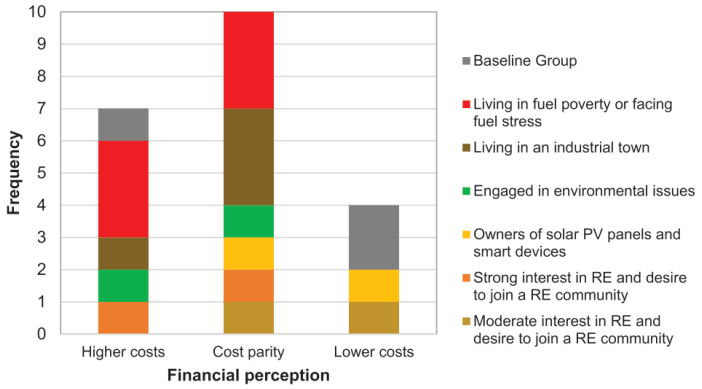

Fig. 11. Consumer perceptions of purchasing costs for hydrogen home appliances.

switch energy provider based on cost benefits, usually doing so on annual basis at minimal inconvenience. At times, the voluntary decision to change had been taken due to poor customer service, as opposed to being "*totally motivated by cost*" (FG1:1). In other instances, respondents had been switched automatically or forced to change provider due to their supplier becoming insolvent.

In total, twelve companies including the traditional 'Big Six'[32] [198, 199] were mentioned by various participants spread out across half of the focus groups (FG1:1, FG3:2, FG3:3, FG4:1, FG4:2, FG4:3 FG6:1, FG6:2, FG10:2), while other respondents confirmed past switchovers without mentioning specific details. Consistent with previous studies [89,161,167], a feeling of dissatisfaction prevailed among the sample, revealing a lack of confidence in the credibility of energy providers. One property owner was candid in their criticism and drew widespread agreement from fellow participants: "*We've got two properties and we've been changed over from Npower to E. on, and from First Utility to Shell Energy, and in the past I've used British Gas, and to be honest, in my opinion, they're all as bad as each other*" (FG4:1). Notably, similar perspectives were captured in the study of Sovacool et al. [89], which reported dissatisfaction among UK consumers due to the perceived gross negligence of certain energy companies.

The business models and profit motives [153,165] of one energy provider were called into question as an exemplar, with other participants in the baseline group echoing this viewpoint, "*I was with SSE, then all of a sudden, I've been changed to OVO and they just seem to be making a quick profit and legging it*" (FG7:1). Furthermore, the same respondent elaborated on the importance of market competition:

> "*After what's happened recently with all these energy companies setting up and offering people a really cheap deal and then going under, I suppose you're taking a bit of a gamble. Because if you change to this company that's just set up and it doesn't work, then you probably won't be able to get your gas supply back as quick if it all goes horribly wrong, compared to being with an established company. I think the big issue is competition. If there's only a few companies, then they can put a higher price than if there are 20 companies*" (FG7:1).

To an extent, attitudes towards switching energy supplier reflect the typology developed within the Ofgem Consumer Survey 2020 (update on consumer engagement with energy) [164], which demarcates six specific consumer profiles described in Table 4. Moreover, this study finds that consumer behaviours and preferences may reflect a combination of different profiles, linking to a range of factors such as customer loyalty, price, competition, and reputation (see Supplementary Note 6). While it is instructive to categorise consumers, it is essential to further understand the specific driving factors behind segmentation, which may imply multi-dimensional perspectives.

Considering a prospective market for hydrogen homes appliances, this analysis identifies nine factors which may influence consumer engagement with energy suppliers and the decision to switch provider. In total, 21 respondents (~36 %) provided statements on this topic, mentioning two factors on average ($N = 40$), as illustrated in Fig. 12. Cost savings emerged as the most critical factor ($N = 10$), followed by reputation and reliability ($N = 6$), while factors such as customer service ($N = 4$) and company values and ethics ($N = 3$) had a secondary influence. Notably, some participants expressed their preference for switching to a hydrogen supplier ($N = 5$), which was typically associated with the call for a more competitive market ($N = 4$).

At the sub-group level, participants living in industrial towns and fuel poor respondents accounted for more than half the references to cost savings, with an equal split between the two groups. This association may be attributed to the higher prevalence of socio-economic hardship across industrial heartlands, reflected by a high representation of fuel poor respondents from industrial parts of Manchester and Chester. Insightfully, one member of the industrial towns focus group underscored the relevance of market acceptance within this context, "*that's an important point about consumer choice and who you want to go with if there's only one leading supplier and your stuck with them, whatever the cost or service*" (FG5:1).

5.6. Preferences for appliance brands and models

Participants broadly agreed that the hydrogen appliance market should offer well-established and reputable brands to support consumer trust and buy-in, as captured in Fig. 13 (see Supplementary Note 7). Having a wide choice, comparable to the current market for natural gas appliances, was prized by most participants, with one respondent envisioning market diffusion reminiscent of the uptake of smartphones [318,319]:

> "*It may take time, but definitely you should be able to walk into Currys*[33] *or look online and buy these appliances just like you do now. The more*

[32] British Gas, EDF Energy, E. ON, Npower, Scottish Power and SSE. Additionally, participants mentioned Bold Energy, First Utility, OVO Energy, So Energy, Shell Energy and Utilita Energy.

[33] An electrical retailer operating in the UK and Ireland, which specialises in white goods, consumer electronics, computers, and mobile phones.

Table 4
Consumer profiles associated with attitudes towards switching energy supplier.

Consumer profile	Characteristics	Illustrative statements
Happy shoppers	• Confident, trusting and engaged with the energy market • On the lookout for the best deal possible and positive about switching	• *I would switch energy supplier to whoever has the cheapest tariff. There's no loyalty involved (FG7:5).*
Contented conformers	• Broadly happy with the status quo and trusting their supplier • Nervous of change and risk averse, with limited engagement in the energy market and little confidence in or motivation towards switching	• *I've heard some horror stories about people changing energy supplier, so I've stuck with what I know really. Especially because we've had this year or last year where companies were failing because of rising price, you would definitely want to know it's secure (FG1:2).*
Savvy searchers	• Confident, experienced and positive about switching energy supplier • Accustomed to comparing prices across multiple internet sites and finding the best deal	• *I would probably switch because it's something that I do anyway … I would look for a hydrogen supplier … I would look for that compatibility and companies that work well alongside each other. I would be looking for something to simplify everything as much as possible, but also to be affordable as well, and to make things easier (FG6:2).*
Market sceptics	• Very low trust in energy companies • Limited engagement in the energy market and low confidence compared to other markets	• *I think it would be quite good for some new companies to come into the utilities space because at the moment and previously, the current companies, the likes of British Gas and E.ON have quite a bad reputation. So, it might just shake it up a bit if some new providers come in (FG4:1)*
Hassle haters	• Easily deterred by the perceived time, hassle and risks involved in switching supplier • *Partially engaged in the energy market and broadly trusting of suppliers*	• *I would stick to whoever I was with to avoid a double disruption (FG7:4).*
Anxious avoiders	• Low engagement in the energy market and limited ability to switch supplier • Unlikely to allocate time towards seeking a better deal	N/A[a]

[a] Based on recorded responses, this study failed to identify a participant characterised as an 'anxious avoider', however this perspective may have been present among the wider sample.
Source: Authors' design based on [164].

houses that have it, the more the market will take off, just like with mobile phones moving from Nokia phones" (FG4:2).

Such responses add weight to the notion that consumers are more likely to support the hydrogen transition if it brings increased market choice [320]. In addition, several participants in the industrial towns group stressed the importance of having a warrantee, of at least ten and up to fifteen years, for purchase to be considered a viable option. Furthermore, brand recognition and reputation were explicitly emphasised as critical to market acceptance:

> "*We all want choice, but we also want recognised brands like Worcester Bosch and others that we would be able to trust … To have just one manufacturer … is not going to be the way to go. I think we need to be able to have choices, whether we want one with a long warrantee, different models, things like that*" (FG9:1).

In response, a fellow participant cautioned against the risk of monopoly power and market failure [321,322]:

> "*You've got to have a choice for it to be market competitive, otherwise you end up with a company that has a monopoly … You need those organisations that have experience in manufacturing this sort of equipment because they've already got the supply chain in order … If it's a brand new start-up with everything from scratch, then forget it. If you can afford to, you choose to have a brand name boiler because you only have one of them and there's no back up*" (FG9:2).

A few participants also flagged potential issues that may arise, should the servicing of hydrogen appliances be tied to the manufacturer. One respondent with contacts in the building trade explained how "*they've all got their favourite companies … I know a lot of mates who are plumbers and love Valliant but won't touch Bosch or Reliant*" (FG3:2), while another participant highlighted associated risks:

> "*I suppose the other issue with friends of mine is that certain companies make it difficult for engineers to service their boiler. They want to use their own gas engineers. So, you could get a situation where they are bringing in this new technology and the gas fitters won't be able to service them*" (FG7:1).

Consequently, several respondents stressed the need for a fairer market for repairs and servicing: "*I don't think you want to be tied to a particular service contract. You want to be able to go out to the market and find Joe Bloggs, and not rely on the manufacturer, otherwise they can charge what they like*" (FG7:5). Reflecting the potential for consumer resistance, concern was voiced over the difficulty of securing a reliable repair service, which is "*a struggle already*" and could be exacerbated if hydrogen appliances become "*a niche market*" (FG5:2). These remarks reflect the current risk that qualified hydrogen technicians could be in short supply, at least during the initial phases of the transition [54,215,323].

5.7. Perceived community benefits, risks, and costs

Respondents framed the divers of community acceptance for domestic hydrogen around environmental, health, and economic benefits. The potential environmental and climate change benefits of hydrogen (e.g. for "*cleaning up air pollution*" FG1:2) were mentioned twice as frequently as health benefits. Economic benefits were the least discussed of the three areas and mentioned tentatively in most cases. One participant speculated, "*… employment opportunities also maybe*" (FG3:3), while another commented, "*you would need engineers to install appliances, so I guess people would have to train to do that*" (FG1:3). Representing an optimistic outlook, a respondent from South Wales detailed positive employment prospects for the local community based on recent activities and developments in the region:

> "*Down here, through all my lifetime there has been basically oil and petrol, three of four refineries within two miles of each other. Two of those have closed, but they have reopened as LNG [Liquified Natural Gas] ones. So, it's all new technology … people are now being retrained to do all the new renewable energy jobs … They're highly paid jobs which we needed because our economy was suffering … now the local people are starting to be retrained. My son works in it now … it's positive news for Pembrokeshire*" (FG4:2).

This narrative reflects how citizens may envision prospective hydrogen futures [86] as a source of "hope for the regeneration and maintenance of a community" [324]. Touching on this aspect, one participant was somewhat optimistic about market developments, "*looking at current gas prices, hopefully reduced costs would be a benefit to local communities*" (FG2:6).

Countering this sense of optimism, a community leader stressed the importance of economic risks:

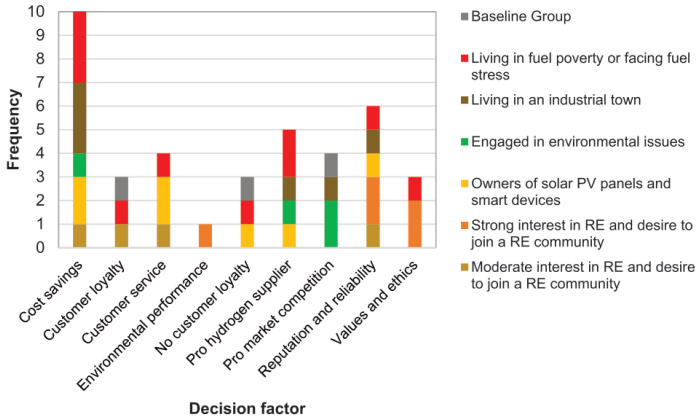

Fig. 12. Factors influencing consumer engagement with energy suppliers.

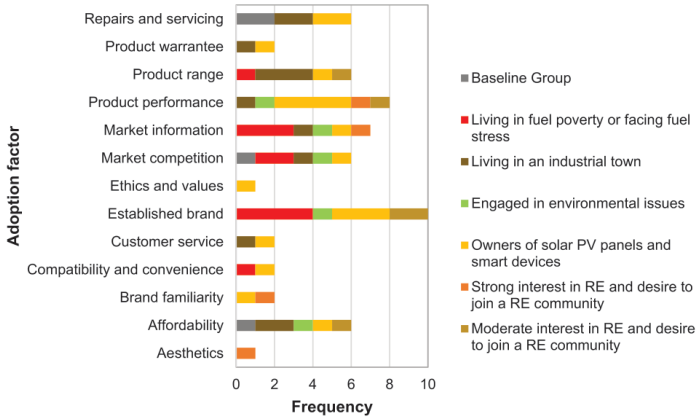

Fig. 13. Factors influencing the potential uptake of hydrogen homes appliances.

"*It's purely based on cost more than anything, so the risks to the community are financial … we live in an area of high social deprivation, so if it cost anybody anymore, then it will just be a no-go*" (FG9:2).

Based on experience working in the retrofit market, a participant from Teesside (Middlesbrough), highlighted the risk of "*potential negativity that could come from a lack of community engagement and buy-in*," associated with "*the failure of the Green Deal*" (FG8:3) and related policies:

"*When I say the failure, I'm not talking about the finance. I'm talking about the installation and accreditation of those installers and the phoenixing of companies that come and go. It's had particularly detrimental effects on lower- income families around the country. There's been unintended consequences of wall insulation which has actually made properties much worse"* (FG8:3).

Supporting this assessment, studies have documented the inadequacies of the Green Deal [325], which failed to improve insulation standards and building performance [326] following a lack of building regulations [327]. It was suggested that more information should be made available to the public, alongside "*meaningful engagement to get to an understanding of what people want and what they fear, and how they can overcome it*" (FG8:3). As a result, the same participant remained sceptical about the foundations of UK's industrial strategy:

"*I think part of the economic system in this country is we need to see growth in industry, so we'll fund something and create jobs, but the overall impact is more likely to be detrimental than productive*" (FG8:3).

This account highlights the importance of both community acceptance and distributional justice, especially in areas with a history of social deprivation such as Teesside [328,329].

In most cases, other risks to the local community related to changes to local infrastructure and associated disruptive impacts were viewed to be negligible. Participants framed these impacts in terms of increased traffic, noise, and disruption to reliable energy supplies. One respondent (FG2:3) contextualised their answer by citing recent experiences with the changeover to fibre optic internet [330,331], but ultimately viewed the hydrogen switchover as a less disruptive proposition at street level. Instead, risk factors were framed in terms of trust and credibility:

"*The risks are the inconvenience of the roads being dug up and all that stuff. I don't see risks, but I see that it's always outsourced to the cheapest*

bidder, so it has to be done by a company that's reputable and accountable. When they say two weeks, it managed properly and doesn't take four months" (FG2:3).

On this theme, one participant mentioned the potential for "*geographical upheaval*" in terms of "*digging up roads*," but downplayed these risks off by declaring, "*… let's face it, the road network is already so abominable, a few extra trenches aren't going to make much more of a difference*!" (FG9:2).

Two participants also shared divergent accounts of infrastructural change in Wales, reinforcing the importance of place attachment and local context [332–335]. Notably, one respondent provided a somewhat cautionary tale based on their experience in the north: "*I remember living on an estate where gas came to the area for the first time, but the level of disruption to the road and network, and the amount of traffic and roadworks, that was going on went on for six to nine months"* (FG5:3). By contrast, a retired tradesperson from South Wales trusted in the governance process: "*The infrastructure doesn't worry me in anyway. It's going to be highly regulated and safe. It's always been that way down in Pembrokeshire. I see it will be well-governed with all the laws*" (FG4:2). Another participant shared this viewpoint, explaining how "*… with the regulation and governance, they're not going to take any risks on this, so from a health and safety perspective it should all be covered*" (FG4:1). Such perspectives have been echoed in several studies [162,163,185,186], with evidence suggesting that public trust in regulation reduces concerns over hydrogen safety risks [73].

5.8. Perceptions of spatial dynamics and energy justice

Following information provision regarding the spatial dynamics of the hydrogen transition, participants were asked follow-up questions concerning choice and fairness. The discussion aimed to gauge consumer attitudes towards three key aspects: (1) geographical inclusion or exclusion in the early phases of the domestic hydrogen transition; (2) related equity implications, such as whether consumers should have a choice about adopting hydrogen appliances following a unilateral conversion of their gas network; and (3) whether they would be willing to pay for the costs of the transition if excluded as end-users.

At the outset, several participants asked for clarification about why specific areas and sites are being selected for demonstration projects of trials [336,337], or otherwise considered as potential candidate towns or cities for hydrogen homes [75]. These queries linked to a consensus that more information is needed about alternative low-carbon energy technologies and decarbonisation pathways. Consequently, in some instances, the emerging spatial dynamics of the domestic hydrogen transition – targeted primarily for the industrial north [75] – led to somewhat polarising responses. A minority of respondents, typically from the South of England, expressed concern over the concentration of hydrogen activities around industrial clusters and potential exclusion, with some calling for more action to curb the carbon footprint of London.

Objections of this nature highlight the potential difficulty of satisfying both southern and northern parts of the UK population, at least in the early stages of a potential transition to domestic hydrogen , which is partially reflected by statements in Table 5. Furthermore, references to the environmental benefits of hydrogen remained predominantly urban-centric, although one respondent form Ipswich (FG4:3) also acknowledged the plight of rural areas. Such perspectives illustrate the potential nuance of public perceptions, which may prove counterintuitive to the expectations of policy makers: envisioning hydrogen as a mechanism for regional regeneration to support the UK's post-Covid economic recovery [50,51,338].

Despite a mix of concern and confusion, the advent of hydrogen clusters drew a broadly positive reception based on the premise of industrial reinvigoration [51]. In total, 17 references[34] were made to one of six perspectives (see Fig. 14), with more than half of responses favouring deployment for the industrial north ($N = 9$), contrasted against deployment for London and the Southeast ($N = 4$). Respondents believed the launch of hydrogen homes "*should be selective*" (FG6:2) and "*logical*" (FG9:2), with one participant acknowledging the viability of

Table 5
Consumer perceptions of the spatial dynamics associated with hydrogen homes.

Location	Illustrative statements
Marston Moretaine, East of England (originally from London)	• *They should start with the places that are the worst polluters. Rather than starting off with London who always get everything, start with Humberside and Manchester and places that are industrial* (FG2:3).
Marston Moretaine, East of England	• *By starting in the north, you're then reducing the entire country's footprint by tackling the worst polluters* (FG2:5).
Pembrokeshire, South Wales	• *I don't know if it would be feasible to get all the infrastructure down to us. I can understand it being in a big city, but where I live in a rural area … is it cost feasible to do it?* (FG4:2).
Ipswich, East of England	• *Big cities need something for the emissions … but our countrysides need the help as well* (FG4:3).
Manchester, Northwest England	• *Think about the balance of the population … they talk about bringing the cost down as its rolled out, but if it's not available down in the southeast or other major urban areas, then I can't see how that cost is going to be alleviated for people* (FG5:1).
Chester, Northwest England	• *It makes sense to have those sort of [hydrogen] hubs because the north is known to be a lot more industrial anyway … a great way to make homes and businesses in industrial towns more energy efficient* (FG6:2).
Manchester, Northwest England	• *It's fairer that certain places have it and others don't, and it's also good for leisure places because of the pandemic … to bring more tourism into a particular town … the community could thrive form that and the economy would probably pick up there* (FG6:3).
Falkirk, Central Scotland	• *It makes sense that hydrogen hubs and homes are concentrated in areas of industrial activities, and I suppose the normal criticism is that it's always London and the Southeast that gets all the investment and everything is first there, so maybe this is part of the levelling-up* (FG7:6).
Marston Moretaine, East of England	• *What about down south? It's all up north and I'm only really involved in my local areas* (FG8:6).
Lincolnshire, East Midlands	• *It seems logical to have your storage facilities in industrial estates like they were historically in the 1990s before they were decommissioned* (FG9:2).
Flint, Northeast Wales	• *It should be used in the locations highlighted rather than being launched as a nationwide project because it will be easier to control and maintain in just a few locations at first. I believe it can go through a test run in these locations to determine if it can go nationwide* (FG9:6).
East London	• *London should be on the list and the top priority because of all the carbon emissions and urbanisation* (FG10:2).
Isle of Wight	• *I think it's better to roll it out through the whole of the UK and not only certain regions because there might be those down South that do want to have this. But there's nothing there from the map at the moment, so there should be more fairness there* (FG10:3).

[34] One participant (FG5:5) held a dual perspective on this aspect.

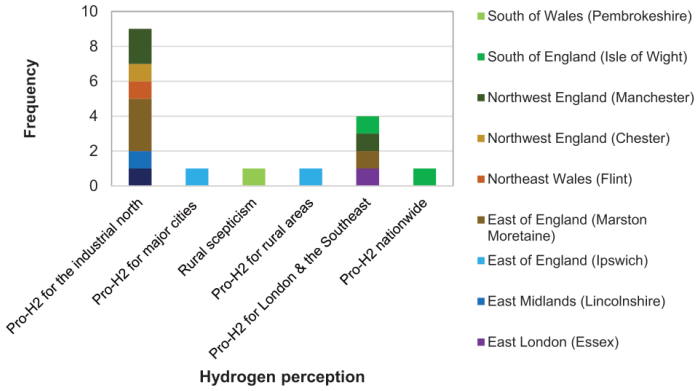

Fig. 14. Consumer perceptions of potential locations for hydrogen homes.

roll-out strategy, despite personal reservations about early adoption:

> "*It's a good thing … looking to implement it area- by-area. In due course by 2035, everyone will have changed over to something. I'm just a bit reluctant to be the first one to try it out … And I would want it to be around for a few years before I got involved in it. I wouldn't want to be the first to try it out and then regret that decision*" (FG10:3).

Reluctance and risk aversion towards adopting new technologies is critical factor of social acceptance, with evidence from Ofgem suggesting UK consumers are more accepting of a familiar or established option [159].

Regarding choice dynamics related to the hydrogen switchover, 21 references were made across the sample corresponding to four perspectives, namely, recognising a 'choice deficit' ($N = 2$), being 'choice agnostic' ($N = 3$) or 'pro-choice' ($N = 10$), and finally, arguing that there is 'no room for choice' ($N = 6$). While close to half of the comments were in favour of choice (see Fig. 15), some respondents were adamant that the switchover should be mandated due to the pressing need to decarbonise [339,340] and the nature of large-scale energy transitions [311,341,342]: "*Did they have a choice when town gas was switched off? No, you've got to do it. It's an entire municipal engineering project. There's no room for choice, it just needs to happen*" *(FG9:2)*.

Speaking from direct experience, another participant mirrored this perspective, "*… we went from coal gas to natural gas. Would it make any difference if we moved to hydrogen? There was no choice at the time and there no charge*" (FG1:4). However, this viewpoint sometimes came into conflict, as reflected in the following perspective:

> "*I'm in two minds about it. I feel like we should not have a choice because we need to make this change. But on the other hand, the price is going to affect us as individuals, so we do need that choice*" (FG10:4).

Representing the pro-choice camp, one respondent argued in favour of deeper levels of consumer engagement to support social acceptance, while cautioning against the risk of exacerbating the North-South divide [343,344] by compromising the levelling-up agenda [338,345]:

> "*If everyone has a choice though, the more people that can buy into it psychologically and emotionally … giving the personal choice is important. I think everyone should have it free or equally, otherwise you have the same issue with the North-South divide. It's all about levelling up and you can't do that if some places don't enjoy the benefit*" (FG2:3).

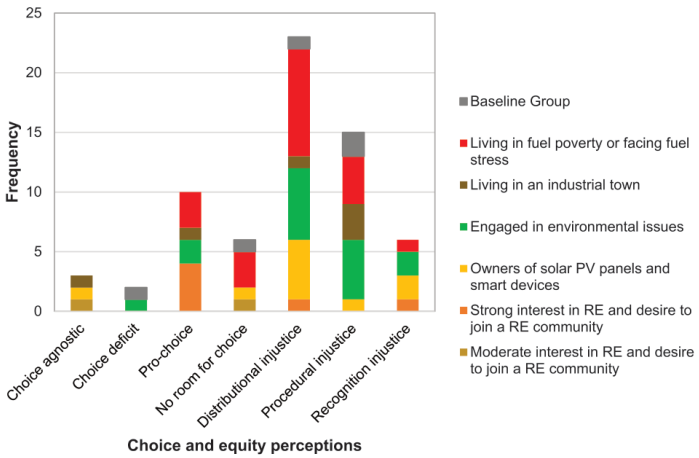

Fig. 15. Consumer perceptions of choice and equity implications.

In many cases, comments on choice dynamics flowed into detailed discussion about equity implications, with the themes of distributional (N = 23), procedural (N = 15), and recognition injustice (N = 6) emerging within most focus groups. As depicted in Fig. 15, references to distributional injustice were twice as frequent as other energy justice aspects, with several insights offered:

> "*You don't want cheaper energy for one part of the country for a long time and other people getting left behind. Maybe you could share out the wealth somehow. If one area is getting cheaper, you could still pass on the savings to other parts of the country*" (FG3:3).

Another respondent highlighted the risk of public resistance and potential backlash:

> "*You can imagine the uproar if they announce that it's only being offered to certain parts of the country due to the exclusion. If they are trying to convince people that it's a good thing … then everyone will want to be included, which doesn't sound like it's possible*" (FG7:6).

Framing things from a similar standpoint, one participant worried about higher costs for early adopters and the risk associated with "*penalising a certain area who are moving over first*" (FG9:1). Moreover, the following critical perspective was supported across parts of the sample:

> "*If there's no chance whatsoever that we are going to benefit from it, why should we pay for it? If the long-term plan is that most of Britain is going to have it, then great, pay for it now through our taxes. But if there are lots of areas that are never going to get it, why should they pay for it then?*" (FG4:2).

Specifically, consumers facing fuel poverty pressures expressed the highest level of concern over distributional injustice (N = 9; 39.1 %) and energy injustice in general (N = 14, 31.8 %), followed by citizens engaged in environmental issues (N = 13, 29.5 %)., who also expressed most concerns over procedural injustice (N = 5; 33.3 %). This result suggests alignment between parts of the population most concerned about energy injustice and climate injustice, respectively. Given the frequency and intensity of comments on this theme (see Supplementary Note 8), it is evident that community acceptance could hinge on how choice architectures [346,347] influence the emerging spatial dynamics, logistics, and equity implications of the transition.

5.9. Perceptions of individual risks and energy vulnerabilities

Following the discussion on community wide impacts and potential disruptions at street level, participants considered their tolerance level for being temporarily disconnected from the gas grid during the hydrogen switchover (see Supplementary Note 9). Fig. 16 shows that the highest frequency of responses included 1–2 days (N = 4), 2 days (N = 4), and 2–3 days disconnection (N = 5), while less than 1 day (N = 2) and up to 1 week (N = 1) emerged as notable outliers among responses (N = 23).[35] Additionally, one respondent offered a unique perspective which circumvented a direct answer and reflected grievances with their current gas connection, "*I'm willing to be disconnected for how long I need to for the purpose of the improvement of the service*" (FG9:8).

Speaking from direct experience, one participant explained the contingencies involved with short-term disruption:

> "*The disconnection aspect depends on the month of the year. I went three days with a gas boiler last January and that's plenty. I wouldn't want to repeat that, and I have a log burner so it could have been worse. At least we had one room that was warm in the house*" (FG1:1).

Acknowledging that tolerance thresholds would depend on the season, respondents agreed that the switchover must be scheduled for the summertime, as it not only "*makes the most rational sense*" (FG10:4), but may help circumvent negative impacts: "*… during the summer, you would feel it less and that's important and a lot better for vulnerable and elderly people and those with disabilities … you need to consider everyone here*" (FG10:3).

Supporting research findings [72,78,163,185], several participants expressed additional concerns over impacts on vulnerable individuals and households during the hydrogen switchover. One respondent underlined how "*you have to take into account people with health problems*, " while another explained that their mother "*has the heating on every single day of the year, so you've got to look at people that are old and vulnerable as well*" (FG9:1). Consequently, tolerance levels were tied to personal circumstances such as household demographics and ability to cope with the disruption.

Reflecting on their recent experience of showering at the gym for "*about four days in summer*" due to a gas leak, one participant shared their view in detail:

> "*The disconnection period depends on people's circumstances. If you've got a family with young children … but you might have someone who can go stay somewhere else for the week … but it's an individual thing really. Some people can deal better with it, but others like the elderly, handicapped or people with children won't be able to*" (FG7:1).

Respondents further suggested how showers could be taken at other places, such as the local swimming pool (FG5:4), or a nearby hotel, if necessary (FG9:1), or preferably at a friend's house (FG3:3).

In addition to scheduling for the summer months and accounting for energy vulnerabilities, participants relayed the need for information provision, communication, and planning to help minimise the length and extent of the disruption, which should be delivered responsibly by involved parties: "*… so if they say for example that you're going to be off for three days, then it would have to take that, not you're going to be disconnected for another week … that would be the crunch really*" (FG1:3). Consequently, some specific mitigating measures were proposed to help manage the disruptive impacts of the switchover, as discussed in Table 6. Additionally, some respondents elaborated on their willingness to tolerate home visits from engineers and technicians during the switchover, which implied disruption for up to a few days would be tolerable in most situations, as evidenced within Table 7.

5.10. Inferences from multigroup analysis

To complete this part of the analysis and consolidate the empirical contribution, five metrics are compared at the sub-group level to derive comparative insights on social acceptance. Fig. 17 integrates two measures of public trust in the government (low and partial), two measures of market acceptance (higher costs and cost parity for appliance purchase), and a combined measured of energy justice (distributional, procedural, and recognition) to assess at-risk dimensions in relation to consumer segments. Cost parity, and to a lesser degree partial trust, are included to account for more neutral perspectives which could potentially undermine social acceptance, alongside overtly negative factors. Additionally, the inclusion of these two metrics increases the total number of measured factors by over 20 % (N = 61 to N = 74).

The following patterns are detected which should be comprehensively evaluated in subsequent large-sample studies including cross-country analyses. Respondents living in fuel poverty or facing high levels of fuel stress, together with participants living in an industrial town, present the highest mean score across the five metrics (M = 1.8), followed by citizens engaged with environmental issues (M = 1.4), and those with strong interest in RE energy and joining a RE community (M = 1.2). Consistent with the notion of a control group, the baseline group ranks below these segments (M = 1.0), but above owners of solar PV and smart home technologies (M = 0.8), as well as consumers with moderate interest in RE and joining a RE community (M = 0.4). While these

[35] This metric was evaluated at the sample level as tolerance levels are considered to be more associated with socio-demographic variables as opposed to various consumer segments.

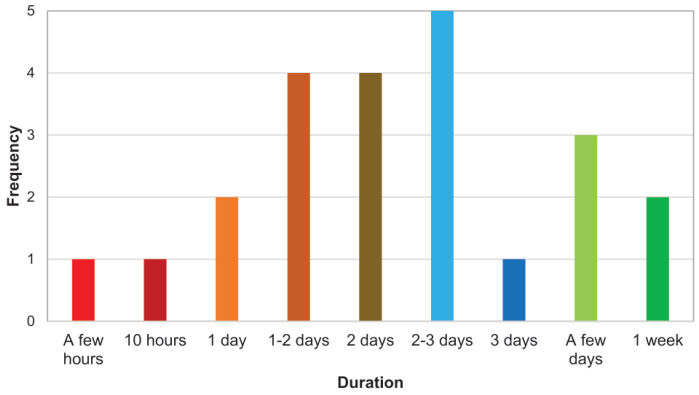

Fig. 16. Tolerance limits for temporary disconnection form the gas grid.

Table 6
Proposed mitigation measures for minimising disruptive impacts and risks.

Participant	Illustrative statements
FG1:5	• *Sufficient warning to either go stay with somebody or to make other arrangements … as long as it was only for a few days maximum because it would indeed be very disruptive to your day-to-day life*
FG4:1	• *I think communication is key. If you can plan for these things … and prepare for it … but I think when it's just landed on you short notice, then it's more challenging. So, I think the positioning and communication would be key for this*
FG5:5	• *They should better inform people about how they can get by without the gas boiler or cooker for a few days during the switchover, with guides about how to get by, so they can see the best way to manage without gas for say two days*
FG9:1	• *I think they do put people who are vulnerable on a certain register, so they are better taken care of during disruptions, but, yes, we need more reassurance about this*
FG9:2	• *Those things [i.e. disruption or burden to energy vulnerable households and others] could be mitigated by surveying different households to see how it would impact them*

Table 7
Attitudes towards engineers and technicians visiting the home.

Participant	Illustrative statements
FG3:1	• *It's no problem for gas engineers and technicians to enter the home, as far as I'm concerned.*
FG3:3	• *It depends on how long they are in the home for, before it becomes a bit intrusive.*
FG4:1	• *I think if they say they're going to need to come in between three to five times, but if it's ten times, it's going to get excessive. So, I think it's all about positioning and having the workers trained so they minimise mess … I think it would be tolerable.*
FG4:2	• *I'm willing to tolerate visits from engineers and technicians until the job is done, as long as its not messy and they tidy afterwards. They've all got jobs to do, and we've all got to make a living. So yeah, I'd be tolerant and … quite happy to put up with a bit of mess and nose to make it more sustainable for the future.*
FG6:1	• *As long as the engineers aren't coming for days and days. You don't mind some disruption if it's the odd day. Will they be digging up the roads?*

findings can be considered exploratory due to the limited sample size, the results reflect the prevalence of fuel poverty in northern regions of the UK, which speaks to the issue of the North-South divide. Consequently, the most at-risk segments for accepting the transition to hydrogen homes may correspond to consumers who are untrustworthy, price pessimistic, and despondent about prospects for energy justice.

6. Critical insights on acceptance dynamics

6.1. Trust deficit recovery

This analysis highlights the extent to which socio-political acceptance is currently hampered by a trust deficit in the government and further stifled by a lack of confidence in energy suppliers, which for some parts of society equates to pervasive criticism and underlying scepticism. At present, trust in these actors remains weak, if not eroded, across many parts of society, following the COVID-19 pandemic and due to the current cost-of-living crisis [348]. Several focus group respondents attested to this reality, while some held out more optimism for positive change, or were otherwise more insulated from socio-economic shocks. More encouragingly, trust in stakeholders such as Ofgem, trade bodies, non-governmental organisations, and research institutes appeared comparatively higher. While divergent perspectives may prevail due to socio-economic and socio-psychological factors, there is a mounting need to address undesirable trust and power dynamics, which continue to subvert the energy transition agenda and potential for a 'just hydrogen economy' [349].

In turn, socio-political acceptance is highly sensitive to the actions of the government and energy companies, which may be dictated by foreign affairs. For example, it remains to be seen how the ongoing Russia-Ukraine conflict [31,32] will impact socio-economic conditions and political stability within the UK. Additionally, unpredictable exogenous shocks such as extreme weather events [350–352] [36] can significantly impact socio-political acceptance over the short-term, contingent upon the reactions of government, industry, business, and media representatives.

Implementing 'hydrogen justice' [353] will require mitigating "the dangers of energy politics" [354], through long-term commitment and observable action towards overturning a legacy of failed energy policies [326,355]. Citizens seek fairness from both the public and private sector when it comes to enacting heat decarbonisation and related net-zero measures, which calls for tangible action across the two main pillars of energy justice [241]. Foremost, principles of fairness and equity – aligned to enacting procedural and distributional justice – should be upheld to foster recognition and restorative justice [239,356,357], especially across industrial heartlands of the UK [114].

In response, corruptive practices, including the subversive aspects of

[36] Notably, two of the focus groups coincided with Storm Eunice (February 14–19, 2022) [351].

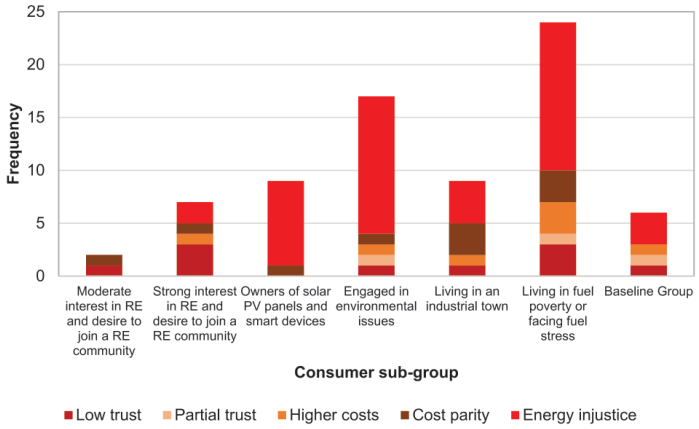

Fig. 17. Potential social resistance to hydrogen homes across consumer sub-groups.

lobbying, should be rooted out in favour of empowering independent statutory bodies, such Ofgem and the Committee on Climate Change (CCC), and prioritising public consultation processes aligned to transparency and inclusiveness (i.e. procedural justice). In tandem, policy makers and stakeholders should support the equitable distribution of costs, benefits, and risks when it comes to enacting the hydrogen switchover and wider decarbonisation agenda, which calls for decisive action on reforming the energy sector (i.e. distributional justice). While the notion of 'deficit recovery' is typically applied to discussions of a financial nature [358], the proliferation of global trust deficits across multiple economic sectors [359–361] marks the urgency for a strategic plan to rebuild a foundational level of public trust in the government and energy industry.

6.2. Price pledges, market competition and consumer choice

Willingness to pay for hydrogen appliances, and by proxy market acceptance, depends on the interplay between purchasing and running costs. However, the former would likely present more of an immediate barrier to consumer uptake, should boiler manufacturers fail to deliver on their current price promise [105]. At present, hydrogen boilers are anticipated to cost less than heat pumps, at least during the initial stages of the transition. While gas-heating may prove a less capital-intensive investment compared to heat pumps, it is apparent that most consumers would resist any price hike, even if hydrogen succeeded in delivering green energy. As a result, there was an underlying consensus that financial security is a stronger motivational driver than perceived environmental benefits.

Given that respondents were not briefed about the recent price promise of boiler manufacturers [105], attitudes towards potential hydrogen adoption proved somewhat positive. There was expectation that hydrogen appliances would not cost much more than current gas appliances, at least for boilers specifically. Should the price promise be delivered, there could be limited grounds for consumer resistance towards investing in a hydrogen boiler; provided there is no obligation to replace a relatively new or well-functioning boiler prematurely, and so long as alternatives such as heat pumps remain somewhat less price competitive.

For owners of relatively new appliances, as well as consumers facing economic hardship, motivating a switch to hydrogen homes would call for a tangible financial incentive, in addition to securing the current price promise. Consequently, the risk of further increases to energy bills is a significant barrier to deploying hydrogen homes, which could undermine the wider 'Gas Goes Green' campaign [362,363]. However, respondents had a lower expectancy that energy bills would increase further if hydrogen were to replace natural gas, whereas appliance purchase was not expected to be cheaper for the most part. Over both the short- and long-term, consumers would need strong assurance that domestic hydrogen adoption would not incur economic losses or impose undue financial risks.

Should cost factors align to expectations, market acceptance will still rest on other aspects of energy markets, namely, the role of suppliers, manufacturers, and retailers. Consumers are wary of the business models and profit motives that drive adverse and irresponsible decision-making; calling for a competitive market environment where both incumbents and new hydrogen-specific suppliers would compete for modest market shares. While the state of the energy market has left consumers with little sense of loyalty, evidence suggests that repeat subscription is plausible so long as reputation, reliability, quality, and customer service remain intact [164,204]. However, consumers are quickly inclined to seek a better deal when one of these characteristics begins to falter.

Mirroring perspectives on energy suppliers, consumers caution against the negative impacts of monopolistic or oligopolistic markets, citing the need for competition and product diversity. Choice is seen as a driver of better product quality and more reliable supply chains, which can help protect customers from limited market access to maintenance and repair services. Compared to energy suppliers, brand name, recognition, and reputation have a stronger influence on decision-making, however, consumers likewise value affordability and reliability, as well as security in the form of a long-term warrantee.

Overall, consumers appear somewhat open to the idea of switching to hydrogen; provided there is a future 'price pledge' of some description on energy bills, which would help support more transparent decision-making on appliance purchase. Although general attitudes towards a prospective market for hydrogen appliances appear mostly positive, this acceptance dimension remains constrained by high levels of dissatisfaction with energy suppliers regarding factors such as cost, reliability, and customer service, which deepen existing trust deficits.

6.3. Hydrogen legitimacy and levelling-up

Community acceptance will hinge on how environmental, social, and economic benefits are communicated and delivered, both to hydrogen and non-hydrogen users. Broadly, there is a sense of support for deploying hydrogen homes across industrial areas as part of the

levelling-up agenda. While respondents may be somewhat unfamiliar with the concept of reinhabiting fossil fuel sites [237], this approach may gain public approval in line with the premise of industrial reinvigoration. Reflecting economic opportunities outlined in the UK Hydrogen Strategy [29], industrial regeneration is more likely to gain public support when retraining and upskilling are delivered to support high-quality jobs for local communities. However, even when economic benefits are anticipated, community engagement and information campaigns remain critical to securing local acceptance.

This study suggests parts of the population may also question the legitimacy of the UK's industrial strategy as a driver of socio-economic benefits. To counteract social resistance, policy makers will need to clearly communicate and justify the emerging spatial dynamics of the prospective transition to hydrogen homes. At present, London and the Southeast, as well as rural areas, are less prioritised in the current heat decarbonisation agenda, at least in respect to hydrogen, which may trigger social resistance due to perceptions of exclusionary policy making.

In view of spatial dynamics and equity implications, government and key stakeholders should aim to leverage prospects for socially acceptable decarbonisation pathways through two key pillars: (1) increasing the social acceptability of hydrogen homes in locations where techno-economic feasibility can be established; and (2) communicating low-carbon alternatives such as heat pumps and district heat networks for locations where hydrogen proves less suitable or unfeasible, in line with the Heat and Buildings Strategy [101]. In terms of the first pillar, the logistical barriers of the switchover were recognised within this study, as demonstrated when discussing choice dynamics, "*I understand people's preference for choice, but a lot of the population wouldn't switch without a nudge, and the infrastructure needs to be there before a choice can even be offered*" (FG8:7). Without delivering on the second pillar, as also reflected by several comments within this study, deploying domestic hydrogen may otherwise risk perverse impacts in terms of aligning with the levelling-up and 'leave no one behind' agendas [364,365].

6.4. Safeguarding against energy vulnerabilities and minimising disruption

Based on a review of the available literature Gordon et al. [73] concluded that the disruptive impacts of the switchover rank as a 'major' barrier to domestic hydrogen acceptance at both the community and household level. However, this study emphasises that disruptive impacts at the community-level are viewed to be less of a concern than the short-term impacts to households, following temporary disconnection from the gas grid. From an overall health and safety perspective, respondents appear relatively confident that adequate regulatory and governance measures will be taken during the switchover period to safeguard against unnecessary disruptions at street level and undue risks.

There is a consensus that disconnection should be capped at a maximum of three days and preferably kept to less than two days. By contrast, tolerance limits appear somewhat higher and more flexible when considering visits to the home from gas engineers and technicians. This divergence reflects the clear distinction between short-term disconnection from the gas grid compared to intermittent disruptions of a human nature. The first scenario may exacerbate energy vulnerabilities and cause direct harm, even if the switchover is carried out during the summer months, while the second situation is primarily associated with minor inconvenience. Respondents appear highly cognisant of this reality, stressing the need to ensure adequate provisions for vulnerable households to minimise negative social and health impacts. Furthermore, the results highlight the potential benefits of consumer engagement on this specific topic, since focus group participants demonstrated a pro-active attitude towards mitigating the impacts of temporary disconnection.

7. Conclusions

This study makes a timely contribution to the discourse on social acceptance for emerging energy technologies, contextualised to the case of domestic hydrogen in the UK. Although this analysis focuses on a specific country case, the findings have international relevance to other nations seeking to transition to green gas for home heating, and possibly cooking, such as the Netherlands, Germany, and Australia. Reflecting the largely global trust deficit in governmental institutions and the energy sector, comments from UK focus group participants are partly generalisable to other populations, such as European neighbours facing energy insecurity following the Russia-Ukraine conflict. Furthermore, through an integrated, mixed-methods multigroup analysis, this research provides a more nuanced understanding of consumer preferences, which may be analysed in subsequent international studies to elucidate cross-cultural findings on energy acceptance.

This analysis provides insights into aspects of socio-political, market, community, and household acceptance related to hydrogen homes, as gauged from the perspective of different consumer groups. The findings reinforce that socio-political and market acceptance are strongly interlinked dimensions of domestic hydrogen acceptance [75]. Principally, persistent consumer dissatisfaction with energy suppliers has eroded the foundations of trust in government and the energy industry for much of society. The profiteering of energy companies against often vulnerable consumers presents a major challenge to changing the status quo, which is aided little by elements of deep mistrust in the central government. Consequently, measures to reform energy markets may prove invaluable to reversing the trend of dissatisfaction with suppliers and establishing the conditions for deploying hydrogen homes in the future.

Synthesising the findings, socio-political acceptance appears the most at-risk dimension, whereas community acceptance is comparatively stronger; following general support for the deployment of hydrogen homes around industrial clusters, which may act as a socio-economic stimulus for local communities. At the community level, consumers perceive hydrogen to offer a somewhat positive vision for the future, while the prospect of linking residential heat decarbonisation to industrial strategy is generally accepted. Evidence also suggests that disruptive impacts are perceived to be tolerable at the community-level and moreover, at the household-level. However, significant uncertainties remain over implementing distributional justice, which entails important implications for deploying hydrogen homes, as reflected by recent events in Whitby village and ongoing developments in Redcar (Northeast England).

There is significant scope to build nationwide acceptance for the low-carbon transition by better communicating the role of green gases and electrification in a net-zero future, so that households can engage more meaningfully as active decision-makers with informed views. Consequently, there are clear opportunities for local actors and stakeholders to engage with driving the residential energy transition as knowledge brokers, which would likely yield a positive multiplier effect on community acceptance and trust. Furthermore, it is evident that consumers will require the hydrogen actor-network to enact commitments towards delivering choice, fairness, and equity. This responsibility includes fulfilling, if not bettering, the current price promise while also endorsing a price pledge on energy costs. In parallel, social acceptance will hinge on how consumers perceive hydrogen's alignment towards alleviating energy poverty and improving the environment.

By extending the evidence base, this study offers strategic insights to support more reflexive decision-making on the role of hydrogen in the energy transition. By analysing patterns in qualitative data, the research identifies causal mechanisms behind social resistance, which should be mitigated to facilitate domestic hydrogen acceptance. Stakeholders can internalise findings from this analysis to leverage potential synergies between social acceptance dimensions, for example by strengthening public trust to improve perceptions of energy justice and corresponding support for hydrogen at the community-level. Additionally, the results

highlight the need to account for consumer heterogeneity in residential decarbonisation pathways, which can be realised by integrating place-specific policies and segment-specific strategies.

This study is the first to operationalise qualitative data from online focus groups into a comprehensive mixed-methods analysis on hydrogen, which integrates both a quantitative and comparative focus. However, until validated by subsequent large-sample survey studies grounded in rigorous statistical analyses, the descriptive results of this small-sample study should be considered as exploratory inferences. Despite some limitations, the richness of qualitative evidence and patterns identified within the quantified data consolidate the importance of several acceptance factors and underscore the relevance of consumer heterogeneity. Ultimately, realising visions for domestic hydrogen futures calls for both techno-economic feasibility and social acceptability, wherein public trust in the government, consumer confidence in energy markets, and community-wide belief in the potential for energy justice are critical components of a prospective transition to hydrogen homes.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualization, Writing – review & editing, Supervision. **Seyed Ali Nabavi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be accessible publicly on our institutional data repository https://doi.org/10.17862/cranfield.rd.20727982.v1, https://doi.org/10.17862/cranfield.rd.21081670.v1.

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Appendix A. Supplementary data

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APPENDIX G: Hopes and fears for a sustainable energy future: enter the hydrogen acceptance matrix

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Abstract

Hydrogen-fuelled technologies for home heating and cooking may provide a low-carbon solution for decarbonising parts of the global housing stock. For the transition to transpire, the attitudes and perceptions of consumers must be factored into policy making efforts. However, empirical studies are yet to explore potential levels of consumer heterogeneity regarding domestic hydrogen acceptance. In response, this study explores a wide spectrum of consumer responses towards the prospect of hydrogen homes. The proposed spectrum is conceptualised in terms of the 'domestic hydrogen acceptance matrix', which is examined through a nationally representative online survey conducted in the United Kingdom. The results draw attention to the importance of interest and engagement in environmental issues, knowledge and awareness of renewable energy technologies, and early adoption potential, as key drivers of domestic hydrogen acceptance. Critically, strategic measures should be taken to convert hydrogen scepticism and pessimism into hope and optimism by recognising the multi-dimensional nature of consumer acceptance. To this end, resources should be dedicated towards increasing the observability and trialability of hydrogen homes in proximity to industrial clusters and hubs, where the stakes for consumer acceptance are highest. Progress towards realising a net-zero society can be supported by early stakeholder engagement with the domestic hydrogen acceptance matrix.

APPENDIX H. Hydrogen homes online survey, October–December 2022

Table H-1. Response rate across sub-samples.

Consumer sub-groups	Number of respondents accessed	Number of completed surveys	Final sample size after data cleaning	Incidence rate after data cleaning	Final incidence rate
BLG	12098	789	677	85.8%	5.6%
MEG and VEG	7950	902 (509; 393)	789 (458; 331)	87.5% (90.0%; 84.2%)	9.9% (5.8%; 4.2%)
FSG	5112	409	379	92.7%	7.4%
Total	25160	2100	1845	87.8%	7.3%

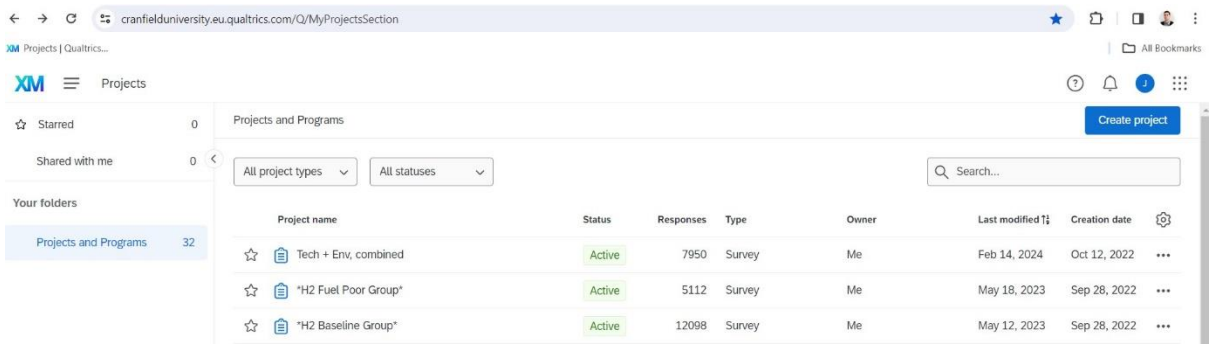


Fig. H-1. Qualtrics record of online surveys.

Table H-2. Hydrogen Homes online survey: Filtering questions and socio-demographic questions

	Filters for entering the survey (bold = continue)	
1	Are you aged 18 or over	• **Yes**/No
2	Which one of the following applies to your home	• **Its' owned outright** • **It's owned with a mortgage** • It's rented from a private landlord, housing association or local authority • Other
3	Do you currently use a gas boiler and gas hob in your home?	• **Yes** • No • Only one
4	What level of involvement do you have in making decision about the purchase of heating and cooking appliances (i.e. boilers and hobs) within your home?	• Zero involvement • Minor involvement • **A moderate level of involvement** • **A high level of involvement** • **Total involvement**
5	How important is being able to choose your heating and cooking technologies?	• Not important at all • Slightly important • **Somewhat important** • **Very important** • **Extremely important**
	Filters for generating consumer sub-groups	
1	Are you currently living in fuel poverty?	• Yes/No[a]
2	What is your level of interest and engagement with environmental issues such as climate change	• 0 – 5 scale (Low to high)
3	When thinking of your response to new energy technologies, which best describes you?	• I have almost no interest in new energy technology and would avoid buying it unless absolutely necessary • I am not very interested in new energy technology but might purchase after it has been on the market for some time • I am somewhat interest in new energy technology but prefer to wait for others to try it first

		• I see potential advantages in new energy technology and like to be among the first to use it • I closely follow new energy technology and am comfortable taking risks by being the first to purchase it
4	What is your level of knowledge and awareness about renewable energy technologies?	• 0 – 5 scale (Low to high)
	Socio-demographic questions for supporting a broadly nationally representative sample	
1	Please indicate your age bracket	• 18–34 • 35–54 • 55 or older
2	What is your gender?	• Male • Female • Non-binary/third gender • Prefer not to say
3	What is your highest level of education?	• No formal qualifications • GCSE-O-Level • Vocational/NVQ • Postgraduate qualification • Degree or equivalent
4	What is your annual income level before tax?	• Less than £14,500 • More than £14,500 but less than £23,500 • More than £23,500 but less than £31,500 • More than £31,500 but less than £41,500 • More than £14,500 but less than £62,500 • I earn no income at present • I prefer not to say

5	How many other people do you live with?	• None, I live alone • 1 • 2–4 • More than 4 people
6	What type of home do you live in?	• Bungalow • Detached house • Flat or apartment • Semi-detached house • Terrace house • Other
7	In which region of the UK do you live?	• Cymru Wales • East Midlands • East of England • London • North East and Cumbria • Northwest • Scotland • Southeast • Southwest • West Midlands • Yorkshire and Humber
8	In which of the following areas do you live?	• Industrial • Inner City • Suburban • Rural • Other

[a] Respondents were provided specific details before answering. For respondents composing the fuel stressed group, the following question was asked:

Are you currently facing fuel poverty or experiencing fuel stress?

- I'm facing fuel poverty (**Qualifies to the survey**)
- I'm not facing fuel poverty, but I'm experiencing fuel stress (*passes to follow-up question*)
- I'm not facing fuel poverty or experiencing fuel stress (**Filtering out**)

Follow-up question:

To what extent do you consider yourself to be experience fuel stress?

	Minimum									Maximum
Fuel stress indicator	1	2	3	4	5	6	7	8	9	10

Responses of ≥5 qualified to the survey for the fuel stressed group.

Please read the following information about fuel poverty:

FUEL POVERTY

Pre-COVID, around 13% of households in England were classed as fuel poor, 25% in Scotland and 12% in Wales. Post-COVID, fuel poverty levels have further increased.

There are three important factors in determining whether a household is fuel poor:

- Household income
- Household energy requirements
- Fuel prices

A household is typically considered **fuel poor** if any of the following applies:

- They are living in a property with a fuel poverty energy efficiency rating of Band D or below
- They spend more than 10% of their income on energy bills
- After spending the required amount to heat their home, they are left with a residual income that's below the official poverty line.

Online survey questions

Q1 How much do you know about **hydrogen fuel**?

Q2 Please provide answers to the following 10 statements about hydrogen.
Please do not guess. It is important we understand **how much you know about hydrogen**.

- Hydrogen can be used to power road vehicles such as buses and cars
- Hydrogen is traded around the world like other energy commodities
- Currently, hydrogen production relies mainly on biomass/bioenergy
- Hydrogen is mainly used in the refining and chemical sectors
- Hydrogen has been used as rocket fuel for space exploration
- Hydrogen is heavier than air
- Hydrogen is an odourless gas
- Hydrogen emits carbon dioxide when burned
- Hydrogen burns with an invisible flame
- Hydrogen cannot be used to store energy produced from other sources

Q3 To what extent do you associate **hydrogen** with the following:

- Bomb or nuclear bomb
- Zeppelins or Hindenburg disaster
- Fuel cell or rocket fuel
- Hydrocarbons or combustion
- Clean energy or zero-emissions fuel
- Hydrogen society or hydrogen economy

There are a range of **low-carbon energy technologies** that may provide an alternative to natural gas for heating and cooking purposes.

Q4 Are you aware of these technology options?

Q5 Are you aware that the UK government has a **Hydrogen Strategy**?

Q6 Are you aware that **hydrogen** may provide a potential low-carbon option for **home heating and cooking**?

INFORMATION ON HYDROGEN PRODUCTION

Q7 How do you feel about the government's **current twin-track strategy**? (i.e. with a role for blue and green hydrogen)

Q8 Please evaluate your **attitude** towards the UK government supporting the following:

- **Blue hydrogen production** in the short-term (i.e. up to 2030)?
- **Blue hydrogen production** over long-term (i.e. beyond 2030?)
- **Green hydrogen production** in the short-term (i.e. up to 2030)?
- **Green hydrogen production** over the long-term (i.e. beyond 2030)?

INFORMATION PROVISION ON HYDROGEN HOME APPLIANCES

Q9 Please evaluate the following statements about a **hydrogen boiler**:
Use your mouse or cursor to adjust the scale on the thermometer
10 represents the highest level of expectation

- I expect a hydrogen boiler to provide **a higher level of thermal comfort** than a natural gas boiler (i.e. satisfactory level and distribution of heat)
- I expect a hydrogen boiler to be **more energy efficient** than a natural gas boiler
- I expect a hydrogen boiler to require **less maintenance and servicing** than a natural gas boiler
- I expect a hydrogen boiler to be **easier to operate** than a natural gas boiler
- I expect a hydrogen boiler to provide **a smarter heating system** than a gas boiler

Q10 Please evaluate the following statements about a **hydrogen hob:**
Use your mouse or cursor to adjust the scale on the thermometer
10 represents the highest level of expectation

- I expect a hydrogen hob to **perform more efficiently** than a natural gas hob
- I expect a hydrogen hob to provide **better cooking control** than a natural gas hob
- I expect a hydrogen hob to be **easier to maintain and clean** than a natural gas hob
- I expect a hydrogen hob to provide **a smarter cooking system** than a natural gas
- I expect a hydrogen hob to offer **a more modern and sleeker look** than a natural gas hob

Q11 What is your expectation for the **purchasing price of a hydrogen boiler compared to a gas boiler**?

Q12 What is your expectation for the **purchasing price of a hydrogen hob compared to a gas hob**?

Q13 What is your expectation when considering potential **energy bills for domestic hydrogen compared to natural gas?**

Q14 Please evaluate your current **safety perceptions** of hydrogen compared to natural gas for the following:

- **Hydrogen boilers**
- **Hydrogen hobs**
- **Hydrogen pipelines (i.e. transport/transmission)**
- **Underground storage of hydrogen gas**

Q15 Overall, how do you perceive the **safety level of hydrogen** compared to natural gas in terms of production, storage, transportation and domestic use?

Q16 To what extent do you **agree** or **disagree** with the following statements:

- Switching from natural gas to hydrogen will have a **negative impact on UK energy security** (i.e. reliability of energy supply)
- Switching from natural gas to hydrogen will lead to **higher levels of fuel poverty across the UK**
- Switching from natural gas to hydrogen will contribute **very little to reaching the UK's net-zero target** (i.e. a reduction of the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050)

Q17 How concerned are you about the following impacts related to **the hydrogen switchover period**?

- Noise, traffic and other potential inconvenience from changes to infrastructure and other hydrogen-related activities at **street level**:

- Being **temporarily disconnected** from the gas grid for up to 3 days in summer: (i.e. during the switchover period)
- Disruption from **engineers and technicians** working within your home during the switchover period: (i.e. up to 3 days)

Q18 Please evaluate your expectations of **hydrogen homes** delivering the following

community benefits (i.e. within those places that switch to hydrogen):

- **Economic benefits** such as job opportunities and income security
- **Social benefits** such as reduced levels of energy poverty and improved health
- **Environmental benefits** such as lower carbon emissions and better air quality

Q19 To what extent would your attitude towards **hydrogen homes** be determined by the following scenarios:

- Your local area is one of the first places to offered hydrogen homes
- Your local area is offered hydrogen homes within the next 10 years
- Your local area is offered hydrogen homes at some point in the next decade (i.e. 2030-2040)
- Your local area is not offered hydrogen homes (i.e. excluded from the switchover)

Q20 How much trust do you have in the following stakeholders when it comes to supporting a cost-effective, efficient and fair transition to **hydrogen homes**?

Trust in government

- **Central government**
- **Regional authorities**
- **Local government**

Trust in the energy sector
Gas distribution network operators are responsible for maintaining, repairing and replacing gas pipes

- **Gas distribution network operators**
- **Natural gas companies**
- **Electricity suppliers/energy companies**
- **Renewable energy producers**

Trust in industry and business
A trade body or association is an organisation that works in the collective interests of its members in a particular industry

- **Trade bodies or Trade associations**
- **Boiler manufacturers**
- **Gas engineers and technicians**
- **Financial institutions**

Trust in other entities
Ofgem is the independent National Regulatory Authority for the electricity and downstream natural gas markets in Great Britain

- **The Office of Gas and Electricity Markets (Ofgem)**
- **The media**

- **Non-governmental organisations**
- **UK Universities**
- **Other research institutes or organisations**

Q21 How important are the following **factors** to your overall attitude towards **hydrogen homes**? (i.e. heating and cooking appliances)

- **Cost factors** (i.e purchasing and running costs of hydrogen appliances)
- **Safety factors** (i.e. safety level of hydrogen heating and cooking)
- **Environmental factors** (i.e. impacts on air quality and climate change)
- **Energy security factors** (i.e. reliability of energy supply)
- **Performance factors** (i.e. reliability and operation of hydrogen boilers and hobs)

Q22 How do you feel about the prospect of using a **hydrogen boiler** and **hydrogen hob** within your home?

- Satisfied
- Calm
- Confident
- Optimistic
- Discontent
- Worried
- Fearful
- Pessimistic

Q23 What is your level of willingness to switch to a **hydrogen boiler** before 2030?

Q24 What is your level of willingness to switch to a **hydrogen hob** before 2030?

Q25 What is your level of willingness to switch to a **hydrogen home** before 2030? (i.e. both hydrogen heating and cooking)

Q26 Please evaluate your **current level of support or opposition** for the following:

- Hydrogen becoming a critical part of the UK's domestic energy future
- Hydrogen replacing natural gas in your local area before 2030
- Switching your home to both hydrogen heating and hydrogen cooking before 2030

INFORMATION PROVISION ON HYDROGEN GEOGRAPHIES

Q27 It follows that **hydrogen homes** are more likely to be located around industrial towns, at least during the early years of the transition.

To what extent does this impact your previous level of support or opposition for **hydrogen homes**?

Q28 Please use this text box to explain more about your attitudes towards hydrogen or any other reflections on this topic.

Information provision materials (as appeared in the survey)

1. Information provision on hydrogen production

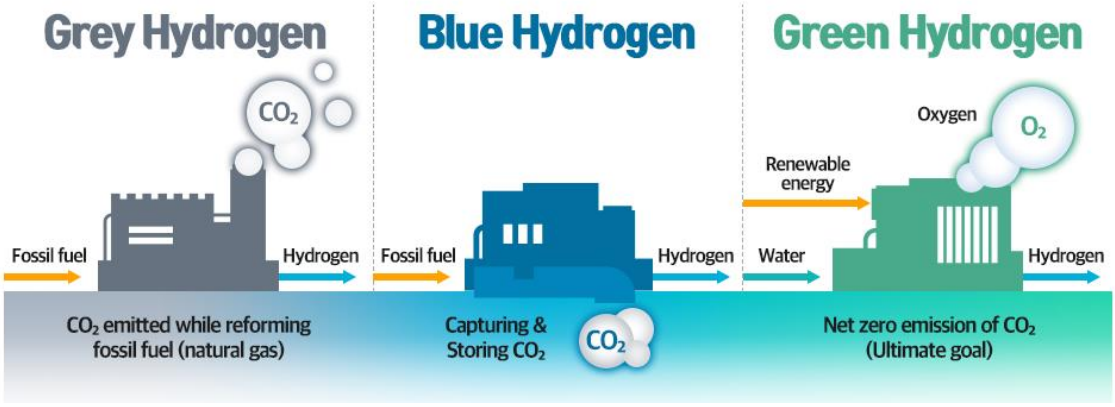
Hydrogen must be extracted from other sources of energy such as fossil fuels, water and biomass. At present, approximately 95% of worldwide hydrogen production comes from fossil fuels, also referred to as '**grey**' hydrogen.

Globally, hydrogen is responsible for just over 2% of all carbon dioxide (C02) emissions per year, which is equivalent to twice the C02 emissions of the entire UK. Developing technologies to produce hydrogen in a clean way is critical to tackling the climate change challenge.

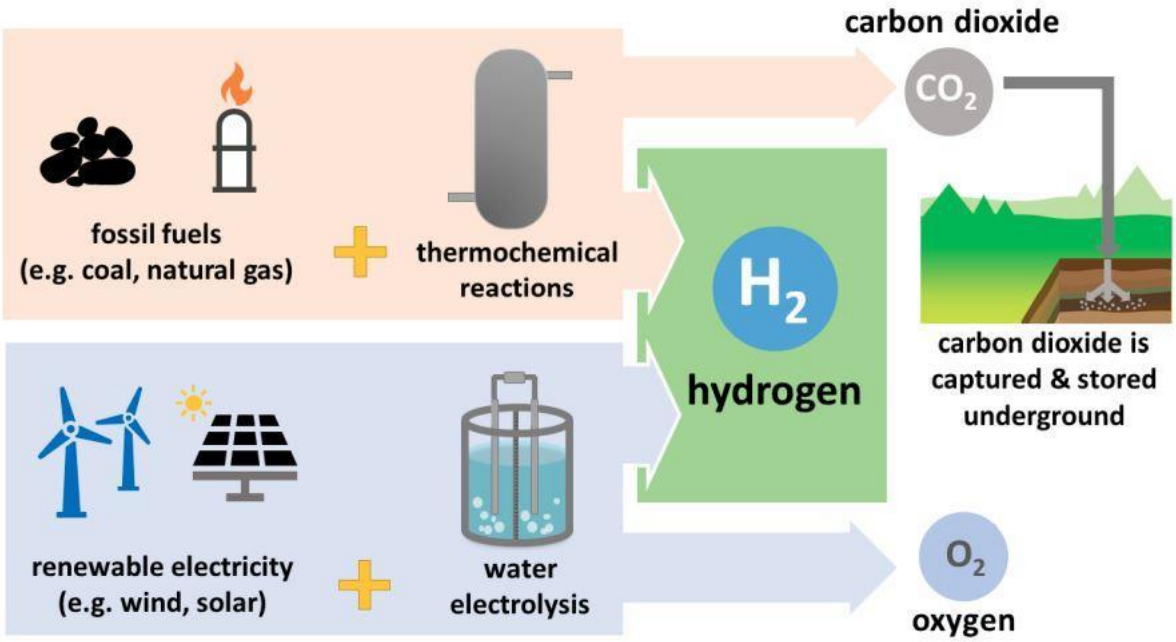
In the UK, there are currently two main **low-carbon hydrogen production pathways**, commonly referred to as '**blue**' and '**green**' hydrogen. The government named this their '**twin-track**' approach in the UK Hydrogen Strategy, which was published in August 2021.

Steam methane reforming (SMR) is a mature technology which has been used for decades to produce fossil-based (i.e. grey) hydrogen at scale. **Blue hydrogen** relies on combining SMR with Carbon Capture, Utilisation and Storage (CCUS) technology, which captures and stores the carbon dioxide (C02) emissions underground. This must be achieved at a high rate of **at least 90%** to be considered low carbon (i.e. blue).

Green hydrogen is produced from renewable energy through electrolysis. It is a process that splits water into its basic elements – hydrogen and oxygen – using an electric current. The electricity used in the process comes from **renewables**. This is a less mature technology than SMR. At present, hydrogen production via electrolysis is somewhat more challenging and expensive to deploy at a large-scale across the UK.



Source: Posco Newsroom



Source: Future Fuels CRC Australia, 2021

In April 2022, the government released the **British Energy Security Strategy**, which doubled the 2030 hydrogen production target (from 5 gigawatts to 10 gigawatts) and made a commitment *to at least 50% '***green***' hydrogen production* (i.e. sourced from renewables).

2. Information provision on hydrogen appliances

Households are a big emitter of greenhouse gases (GHGs), accounting for 26% of total emissions in the UK, on a residency basis. Cooking accounts for around 2% of total UK carbon emissions, compared to around 14% for home heating, most of which comes from gas boilers. At present, nearly 85% of UK residential buildings use gas central heating.

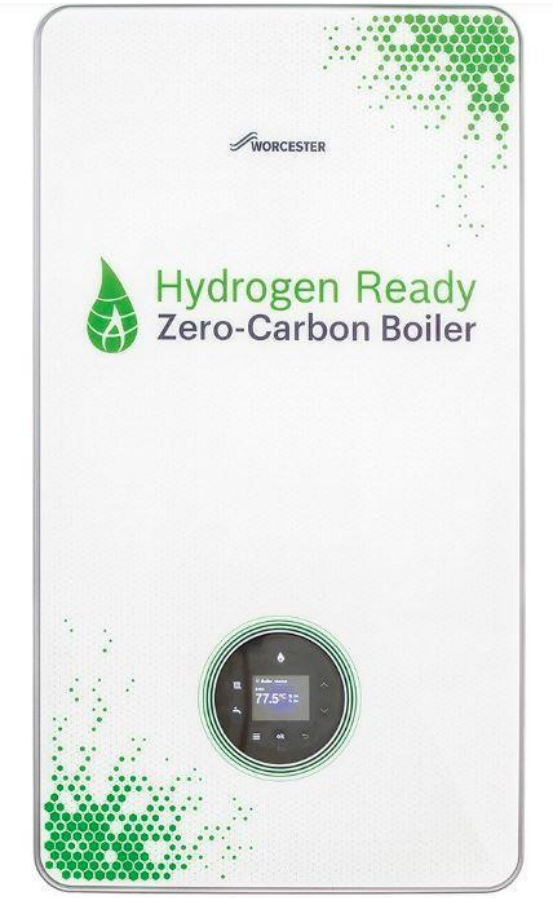
A '**hydrogen home**' refers to replacing natural gas appliances with low-carbon **hydrogen boilers** and **hydrogen hobs** to help tackle **climate change**. This is usually discussed by policymakers in terms of the **energy transition** and **decarbonisation agenda**.

Trials for **hydrogen heating and cooking** have already been conducted at demonstration sites such as the one shown below (Spadeadam, Northumberland). Trials in properties representative of the UK housing stock are currently ongoing at neighbourhood and village scales, with plans for a **hydrogen town trial** before the end of the decade. The UK government will make a final decision on the town trial by 2026.

Source: Envirotech Magazine, 2021

The UK's largest boiler manufacturers – *Worcester Bosch, Vaillant, Baxi and Ideal* – recently announced that new boilers will be built to meet a **'hydrogen-ready' standard**. This means **new boilers** will be able to run on natural gas but can then be easily modified by gas engineers to run on **100% hydrogen**. This modification should take no longer than two hours. According to some industry estimates, *hydrogen-ready boilers* should be available from 2023-2025.

This is a stepping stone in the journey towards phasing out natural gas boilers in the UK. If the gas supply switches to 100% hydrogen, boiler manufacturers will discontinue the production of *hydrogen-ready boilers,* and instead sell **hydrogen boilers**. Manufacturers state that **new hydrogen boilers** should provide somewhat of a 'like-for-like replacement' for existing boilers.



Source: Custom Heat 2020

Because hydrogen is an invisible gas, **colourants** will need to be added to make the flame visible, alongside safety sensors to help alert users when the flame is on.

Currently, hydrogen hobs being tested in trials and demonstration projects burn with an **orange flame**. Like natural gas, hydrogen is also odourless. Therefore, an odourant will need to be added to ensure leaks can be detected. However, unlike natural gas, **hydrogen does not produce carbon monoxide**.

Source: Elemental 2021

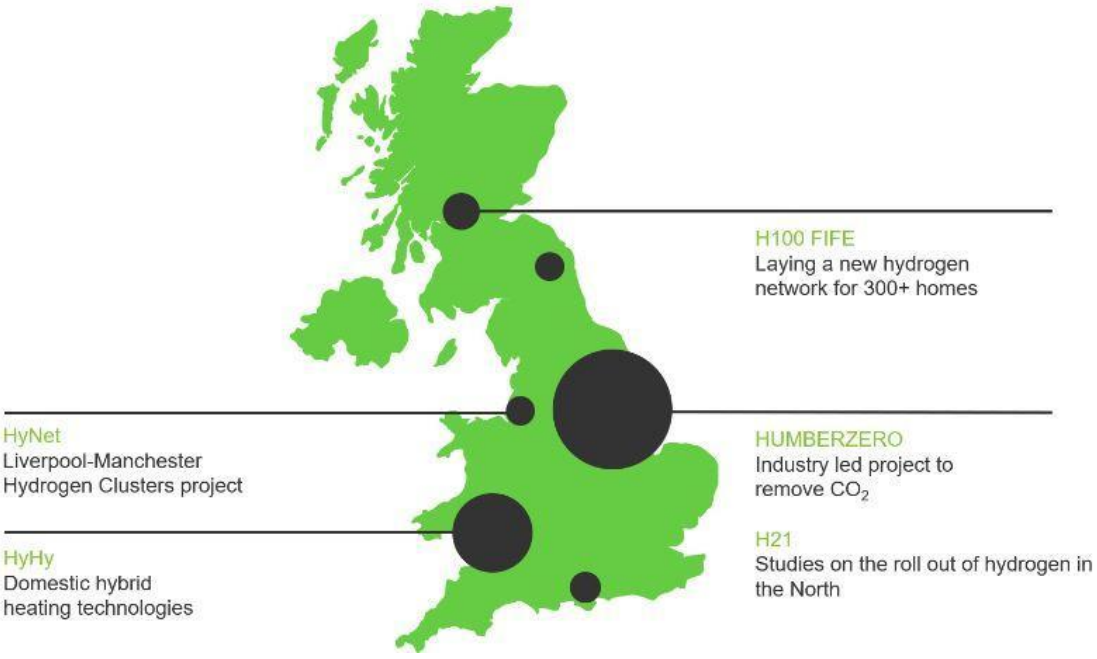
3. Information provision on hydrogen geographies

The **UK Hydrogen Strategy** is strongly linked to the government's industrial strategy, which aims to decarbonise some of the country's **largest industrial clusters**.

Some of these are shown below, with the black dots representing the **size of emissions** (i.e. the East Coast Cluster which links Humber and Teesside has the largest emissions). Locating hydrogen homes around such areas will lead to the development of '**hydrogen clusters**' and regional '**hydrogen hubs**'.

The UK government has stated that the broader **'hydrogen economy'** will help support the following:

- Creation of high-quality, inclusive and sustainable jobs, alongside apprenticeships and re-skilling programme
- Industrial and regional growth in support of the 'levelling up' agenda, local economic benefits and decarbonisation
- 9,000 jobs by 2030, with around a quarter of these jobs potentially driven by British supply chain exports
- Up to 100,000 jobs across the UK by 2050



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APPENDIX I. Results from the hydrogen homes online survey

This Appendix reports the results from the online survey in chronological order.

Knowledge and awareness

The initial survey questions focused on aspects of knowledge and awareness related to hydrogen. Firstly, subjective knowledge was evaluated to establish a baseline assessment of respondents' self-rated understanding of hydrogen. Thereafter, respondents were asked to identify whether ten statements about hydrogen were true or false, as a means of assessing objective knowledge. Finally, hydrogen awareness was explored through three additional questions.

Subjective knowledge of hydrogen fuel

Survey respondents were asked the following questions: *How much do you know about hydrogen fuel*? Answers were recorded on a five-point Likert scale (1 = *I know nothing about hydrogen fuel but may have heard something about in the past*; 5 = *know a significant amount about hydrogen fuel and feel very confident explaining information about it*).

Across the full sample, respondents answered to the effect of *knowing a little about hydrogen fuel and understanding some basic details* (*M* = 2.05, *SD* = 0.97). The result broadly aligns to evidence in the literature including data collected by the Department of Business, Energy & Industrial Strategy [2] in Spring 2022 (N = 4372).[1]

The variance in responses was accounted for by the Very technology and environmentally Engaged Group (hereafter VEG) expressing higher levels of subjective knowledge (*M* = 2.81, *SD* = 1.08) compared to the Baseline Group (hereafter BLG), which had the lowest self-perception of hydrogen knowledge (*M* = 1.73, *SD* = 0.82). Consequently, respondents experiencing fuel stress or having moderate levels of technology and environmental engagement also expressed higher levels of subjective knowledge than respondents in the BLG. [2]

[1] BEIS found awareness of hydrogen fuel to be relatively low when measured on a similar five-point scale (*M* = 2.44, *SD* = 1.11), while awareness of hydrogen's potential future uses to reduce emissions proved comparable (*M* = 2.34, *SD* = 1.09) [2].

[2] The Moderately technology and environmentally engaged Group (MEG) ranked 2nd (*M* = 2.07, *SD* = 0.89), while the Fuel Stressed Group (FSG) ranked 3rd (*M* = 1.93, *SD* = 0.85).

It follows that subjective knowledge of hydrogen fuel is likely to increase when consumers are more engaged in technology and the environment (see Fig. I-1). Nevertheless, even for respondents composing the VEG, their current self-perception corresponds to *knowing a moderate amount about hydrogen fuel and being able to explain some basic information about it*. The findings reinforce the extent to which hydrogen remains relatively unfamiliar to most parts of society [3]. Foreseeably, increasing public awareness of net-zero and the low-carbon energy transition would lead to higher levels of engagement with the hydrogen economy and emerging use cases such as hydrogen homes.

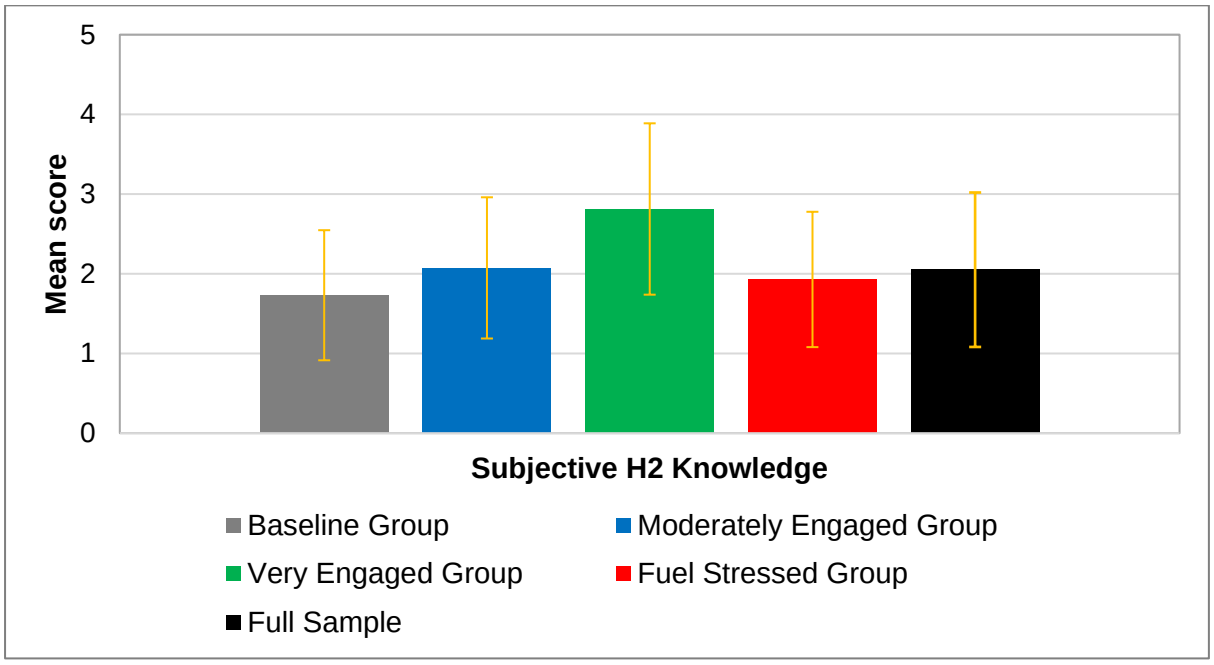


Fig. I-1. Subjective hydrogen knowledge levels across the sample and by sub-groups.

Objective knowledge of hydrogen

Survey respondents were asked ten questions to assess their objective knowledge of hydrogen. Each question consisted of a statement about hydrogen that was either true or false, and respondents were instructed *Please do not guess*. The assessment included five general knowledge questions, followed by five questions with a more scientific or technical focus (see Table I-1). The rationale was to evaluate a wide range of questions, while testing to see whether some aspects of hydrogen were significantly better understood than others.

Across the sample, respondents typically answered 3 to 4 questions correctly (M = 3.38, SD = 2.16), as illustrated in Fig. I-2. Aligning to the findings on subjective

knowledge, the VEG demonstrated the highest level of objective knowledge across the sub-groups (*M* = 4.51, *SD* = 2.21), followed by the Moderately technology and environmentally engaged Group (hereafter MEG: *M* = 3.78, *SD* = 2.05), the Fuel Stressed Group (hereafter FSG: *M* = 3.14, *SD* = 2.33) and the BLG (*M* = 2.17, *SD* = 1.81).

Critically, the findings emphasise the underlying knowledge gap concerning hydrogen, as reported across the BLG in particular. It follows that factual understanding of hydrogen is extremely low. The existing knowledge deficit highlights the extent to which current public perceptions may be derived via subjective inferences and imagery, as opposed to verified evidence. Principally, media representations are likely to be the primary source of knowledge for most consumers, which may present a significant barrier towards developing 'informed beliefs about hydrogen technologies', as highlighted by Scovell and Walton [4] in the Australian context.

Interestingly, general knowledge (*M* = 31.40%, *SD* = 19.58) and technical knowledge (*M* = 36.54%, *SD* = 15.01) of hydrogen, as formulated in the online survey design, proved comparable. The finding implies that consumers have similar levels of knowledge about the hydrogen industry or hydrogen economy compared to scientific understanding. Based on qualitative responses to the online survey [5], respondents typically cited secondary school education as a source of hydrogen knowledge, which was also mentioned by online focus group participants [6].

In terms of the reported knowledge deficit, only 13.5% of respondents knew that *hydrogen is not currently traded around the world like other energy commodities*, while 11.5% answered correctly by identifying that *hydrogen production does not rely mainly on biomass or bioenergy*. Additionally, just 19.3% of respondents were aware that *hydrogen can be used to store energy produced from other sources*. This lack of fundamental knowledge is noteworthy, since one of the main advantages of hydrogen is its potential for acting as an 'energy storage medium' [7].

By contrast, 60.5% or respondents knew that *hydrogen is an odourless gas*, 56.8% answered correctly that *hydrogen can be used to power road vehicles such as buses and cars*, while 44.4% also knew that *hydrogen has been used as rocket fuel for space exploration*. Such observations demonstrate that publicising parallel developments across the broader hydrogen economy (i.e. industry and transport) will play an

important role in raising knowledge levels across society in the context of hydrogen homes. To this point, it is telling that only one-third of respondents answered correctly that *hydrogen does not emit carbon dioxide when burned*. From a climate change perspective, understanding in this critical area would need to be enhanced if consumers are to support the 'gas goes green' campaign [8].

Table I-1. Survey response to factual questions on hydrogen fuel.

Factual statement on hydrogen	Correct answer	Correct response (%)
Hydrogen can be used to power road vehicles such as buses and cars	True	56.80
Hydrogen is traded around the world like other energy commodities	False	13.49
Currently, hydrogen production relies mainly on biomass/bioenergy	False	11.49
Hydrogen is mainly used in the refining and chemical sectors	True	30.79
Hydrogen has been used as rocket fuel for space exploration	True	44.44
Hydrogen is heavier than air	False	30.73
Hydrogen is an odourless gas	True	60.49
Hydrogen emits carbon dioxide when burned	False	34.25
Hydrogen burns with an invisible flame	True	37.94
Hydrogen cannot be used to store energy produced from other sources	False	19.30

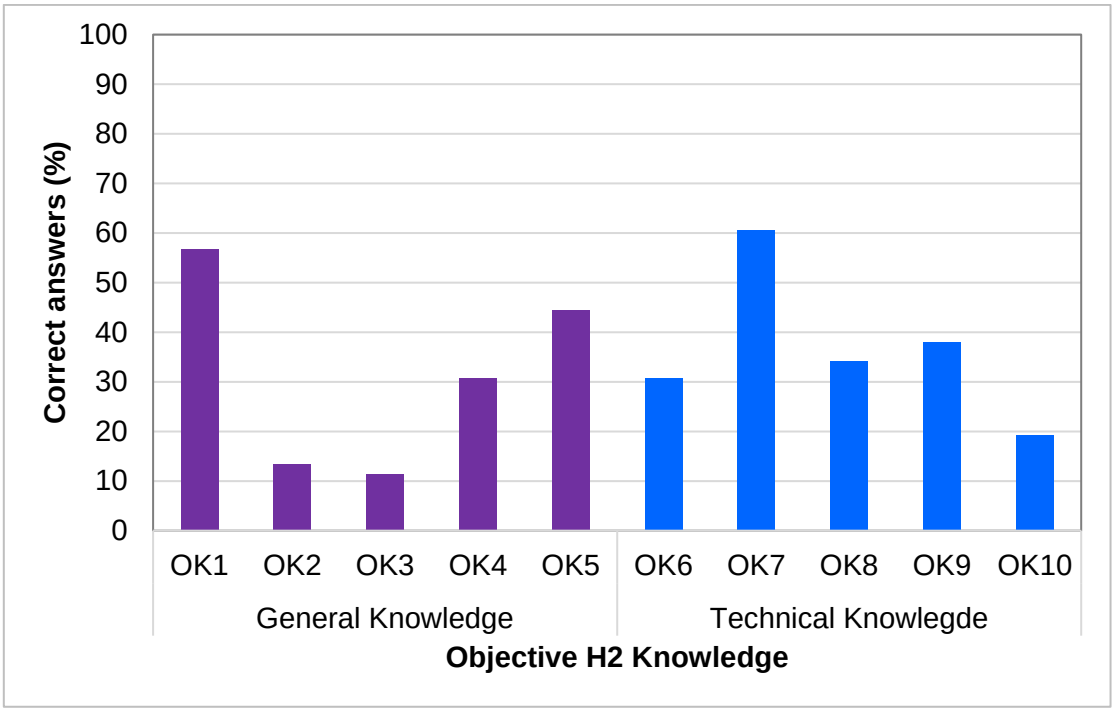


Fig. I-2. Objective hydrogen knowledge levels across the sample.

Based on qualitative responses to the online survey, knowledge emerged as one of the primary factors shaping domestic hydrogen acceptance.[3] Critically, *knowledge deficit* is the second strongest predictor of consumer heterogeneity, ranking behind *environmental benefits,* as reported in Gordon et al. [9]. The largest statistically significant difference was observed between the BLG and VEG ($p < 0.001$, $r = 0.22$), with the VEG having the lowest knowledge deficit. The observed relationship reaffirms a positive association between hydrogen knowledge and environmental and technology engagement [10–13].

When confronted with a knowledge deficit or faced with highly complex or technical information, consumers may bypass deep cognitive evaluations in favour of emotional responses which can act as decision-making heuristic [14]. In accordance with findings in the literature [15,16], it follows that domestic hydrogen remains largely at the periphery of public thinking [17,18], which may constrain the influence of knowledge (and awareness) on social acceptance during the formative phase of the transition.

Hydrogen awareness

Following questions on subjective and objective knowledge, survey respondents were asked three questions to evaluate their overall awareness of hydrogen. Firstly, the following statement was provided ahead of questioning: **There are a range of low-carbon technologies that may provide an alternative to natural gas for heating and cooking purposes**. Accordingly, respondents were asked about their awareness level regarding relevant technology options, as measured on a five-point Likert scale (1 = *No, I was unaware before today*; 5 = *Yes, I'm extremely aware*). Across the full sample, respondents proved less than slightly aware ($M = 1.69$, $SD = 0.30$).

In the follow-up questions, respondents were asked about their awareness level regarding the *UK Hydrogen Strategy* ($M = 1.95$, $SD = 0.41$) and *hydrogen providing a potential low-carbon option for home heating and cooking* ($M = 1.96$, $SD = 0.45$), with results suggesting consumers are slightly aware of hydrogen across the sample. It remains undetermined why the initial response returned a somewhat lower score, however, this discrepancy may be attributed to respondents being unaware of multiple

[3] Specifically, a *knowledge deficit* concerning hydrogen proved the foremost negative sub-factor when evaluating written statements (i.e. 10.1% of responses), while respondents also expressed a *pro-information* perspective (i.e. 7.6% of responses).

technologies beyond hydrogen and answering to this effect. Nevertheless, Fig. I-3 confirms clear trends in participants responses across the three metrics (*M* = 1.87, *SD* = 0.44).

At the sub-group level, the VEG expressed the highest level of hydrogen awareness (*M* = 2.57), followed by the MEG (*M* = 1.89), the FSG (*M* = 1.79) and the BLG (*M* = 1.55). The results further substantiate the evidence regarding low levels of subjective and objective hydrogen knowledge, in addition to demonstrating group-specific differences, foremost in relation to the VEG and BLG.

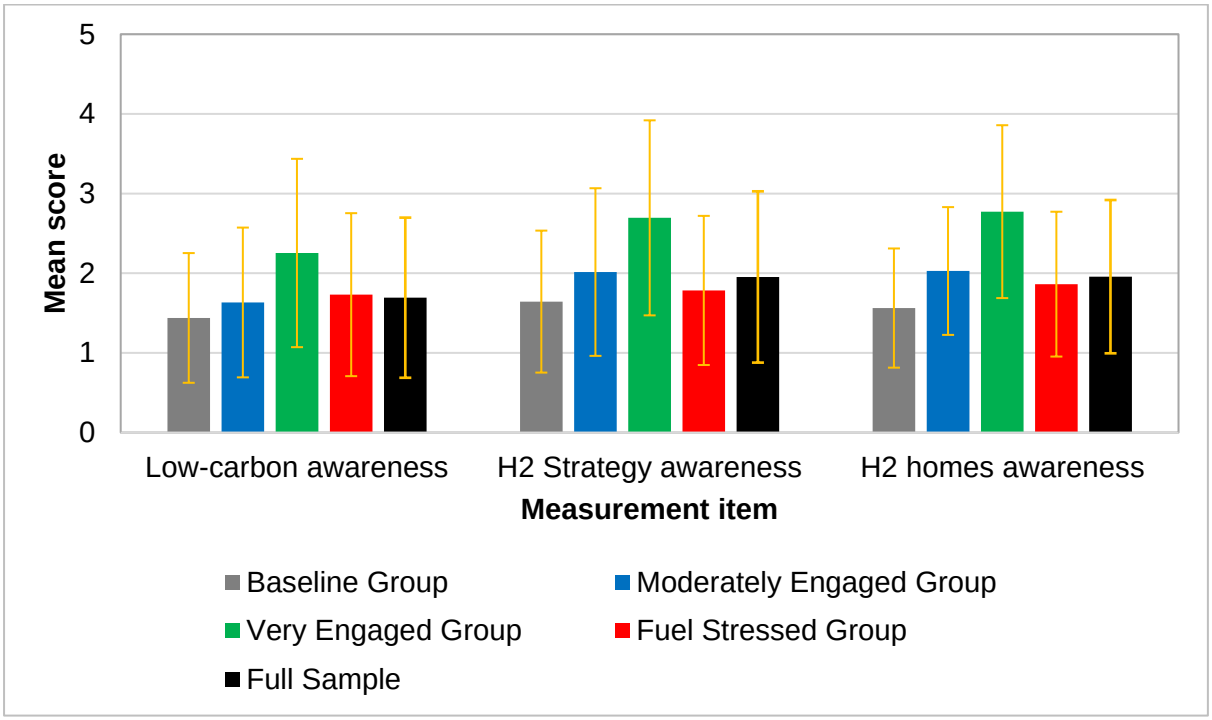


Fig. I-3. Hydrogen awareness levels across the sample and by sub-groups.

Social representation

Between answering questions on objective hydrogen knowledge and awareness, respondents were asked the following question to better gauge the current social representation of hydrogen[4]: *To what extent do you associate hydrogen with the following*? The options were split equally between negative representations (i.e. *bomb or nuclear bomb*, and Zeppelins or Hindenburg disaster), neutral representations (i.e. *fuel cell or rocket fuel*, and *hydrocarbons or combustion*) and positive representations (i.e. *clean energy or zero-emissions fuel*, and *hydrogen society or hydrogen economy*).

[4] The results are reported here in a stand-alone section to support a more fluid the discussion of knowledge and awareness in the first section.

The aim was to explore a wide range of perspectives, as evaluated via a five-point Likert scale (1 = *No extent*; 5 = *Very significant extent*).

Overwhelming, the results showed that a mix of negative, neutral and positive perceptions of hydrogen prevail in the public consciousness, with minimal degrees of separation, as shown in Fig. I-4. Across the sample, respondents identified with each aspect to a moderate extent (*M* = 3.27, *SD* = 0.04). At the sub-group level, a positive social representation was marginally more prominent (*M* = 3.27) compared to a neutral representation (*M* = 3.25), followed by a negative representation (*M* = 3.19). However, there was minimal levels of variance between perspectives within groups (BLG: *SD* = 0.09; MEG: *SD* = 0.13; VEG: *SD* = 0.19; FSG: *SD* = 0.04). Moreover, it should be emphasised that responses to individual framings converged to a strong extent across the four sub-groups.[5]

Fig. I-4. Suggests that the VEG associates hydrogen most strongly with clean energy or zero-emissions fuel, which is also true for the MEG albeit to a smaller degree. Both the BLG and FSG express a comparatively stronger association with a hydrogen society or hydrogen economy (both within and between groups), although the within group difference is relatively small as outlined. One notable outlier in the results is that the MEG is consistent is reporting a weaker social representation across all metrics, falling below a *moderate extent* (i.e. *M* = 3.00) in all cases (*M* = 2.81, *SD* = 0.13). While there is no specific explanation to account for this discrepancy, barring follow-up analysis, the result reinforces the extent to which the social representation of hydrogen remains in flux and could be strongly shaped in either a positive or negative direction, contingent on technological developments, policy making and media reports.

[5] Bomb or nuclear bomb and Zeppelins: *M* = 3.18, *SD* = 0.32; Hindenburg disaster: *M* = 3.20, *SD* = 0.35; Fuel cell or rocket fuel: *M* = 3.28, *SD* = 0.34; Hydrocarbons or combustion: *M* = 3.21, *SD* = 0.32; Clean energy or zero-emissions fuel: *M* = 3.32, *SD* = 0.25; Hydrogen society or hydrogen economy: *M* = 3.21, S*D* = 0.49).

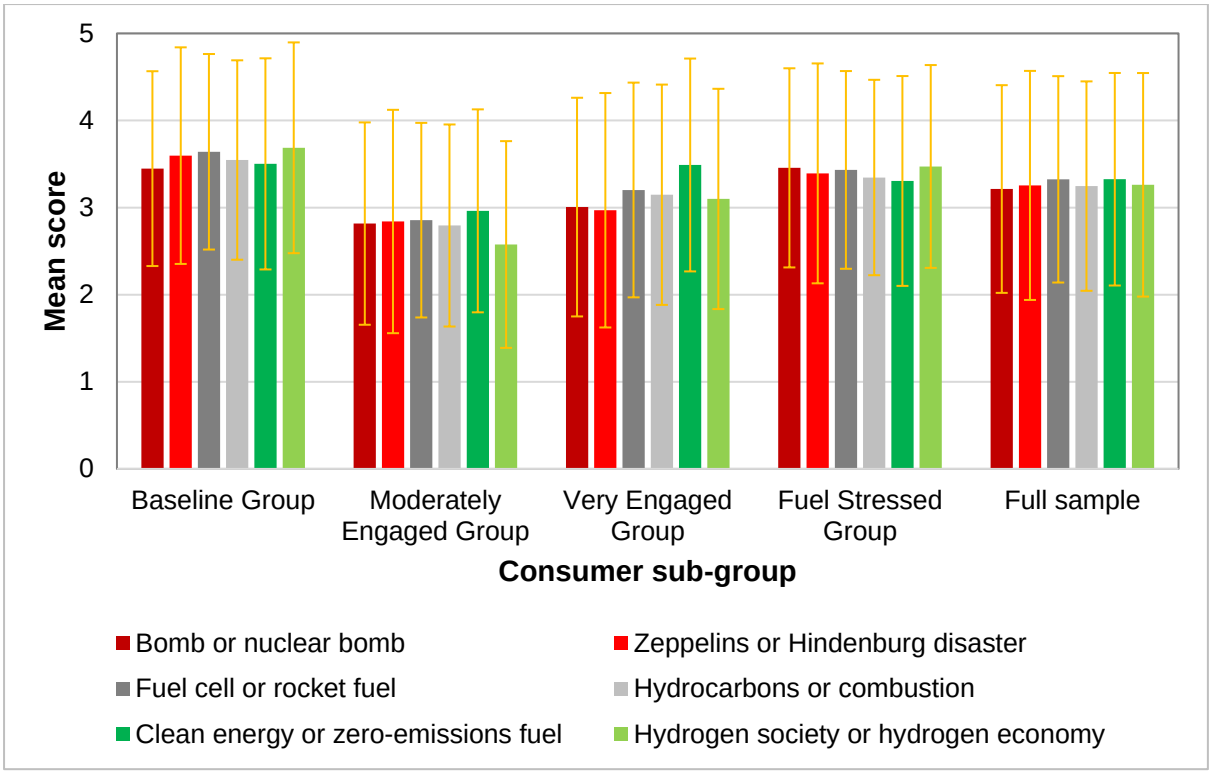


Fig. I-4. Social representation of hydrogen fuel across the sample and by sub-groups.

Perceptions of hydrogen production pathways

Two pieces of information provision were provided to respondents regarding hydrogen production, supported by the following statement:

In April 2022, the government released the British Energy Security Strategy, which doubled the 2030 hydrogen production target (from 5 gigawatts to 10 gigawatts) and made a commitment *to at least 50%* 'green' *hydrogen production* (i.e. sourced from renewables).

Subsequently, survey respondents were asked to firstly evaluate their general attitude towards the government's twin-track strategy, as measured on an acceptance scale ranging from 0 to 10 (i.e. opposed to supportive).

Results indicate that the public has a somewhat neutral attitude towards the government's hydrogen production strategy (M = 5.68, SD = 1.82). By contrast, blue hydrogen (M = 6.17) and above all, green hydrogen (M = 6.86) received stronger support compared to the twin-track approach. However, support across the sample was strongest for green hydrogen production in the short-term (i.e. before 2030: M = 7.28, SD = 0.70), followed by blue hydrogen in the long-term (i.e. after 2030: M = 6.78, SD = 0.69), green hydrogen in the long-term (M = 6.44, SD = 0.72) and finally, blue hydrogen in the short-term (M = 5.57, SD = 0.40).

At the sub-group level, across the five measurements (see Fig. I-5) the VEG registered the highest support level (*M* = 7.24, *SD* =0.88), followed by the MEG (*M* = 6.60, *SD* = 0.81), the FSG (*M* = 6.02, *SD* = 0.62) and the BLG (*M* = 5.93, *SD* = 0.66). As a result, there is strong evidence that engagement in technology and the environment positively predicts support for hydrogen production in the UK context.

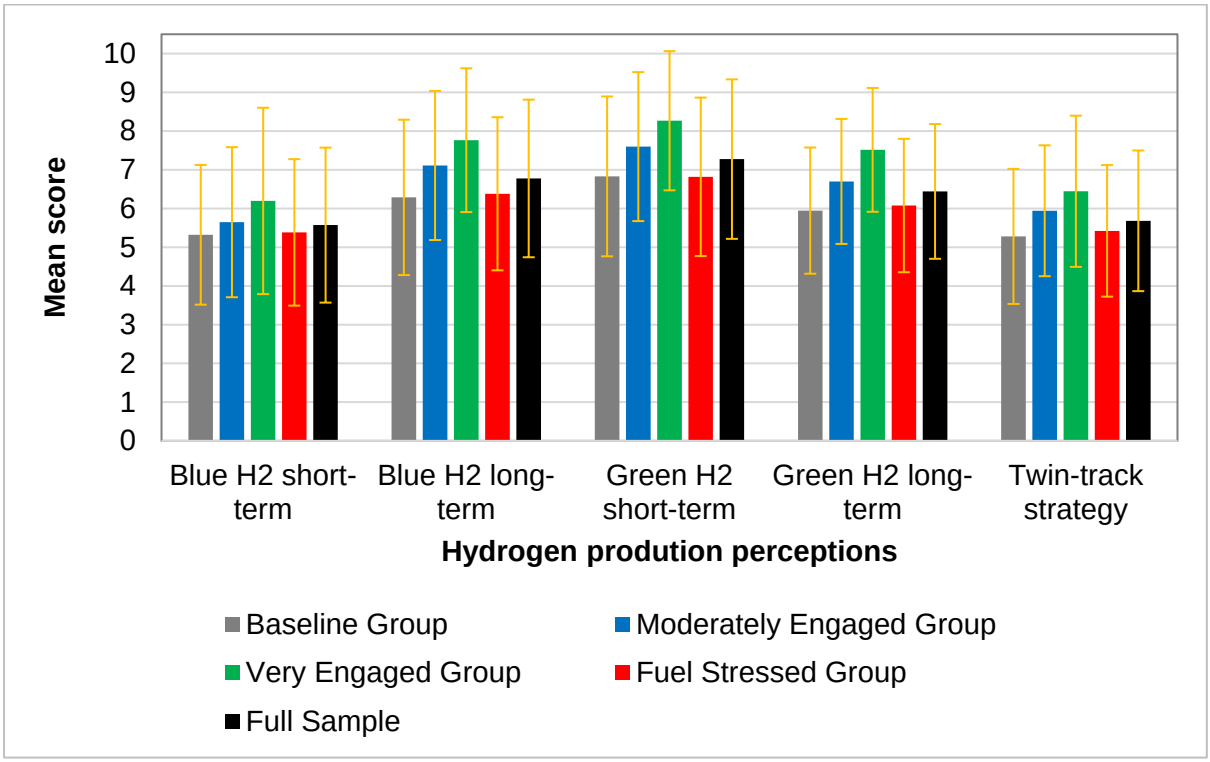


Fig. I-5. Perceptions of hydrogen production across the sample and by sub-groups.

Implications of findings on hydrogen production perceptions

Following the logic of the twin-track approach [19], the reported trends are counterintuitive since blue hydrogen is anticipated to play an enabling role for scaling up a green hydrogen economy [20]. Consequently, an inverse phenomenon is observed regarding public perceptions of the temporal dynamics of the twin-track approach.

One explanation for the observed trend may be traced to relatively high levels of support for carbon capture and storage, as measured by BEIS (N = 4145)[6] [2]. It may be inferred that current perceptions of CCS could imply a somewhat positive outlook

[6] 13% and 31% of respondents expressed 'strong support' and 'support' for CCS. Additionally, 19% were unable to give an answer (i.e. don't know), while 28% held a neutral attitude. Furthermore, 89% of respondents believed CCS would help combat climate change and reduce carbon emissions [2],

towards blue hydrogen. However, based on the results, securing social acceptance for hydrogen homes lies more directly with increasing green hydrogen production, which aligns to most international findings [13,21,22].

It follows that the inferred equivalence or balancing of the twin-track approach appears largely unrecognised or misunderstood by the public. Notably, findings from online focus groups caution that parts of the UK public may see the twin-track production strategy [19] as non-committal to mitigating climate change due to concerns raised over blue hydrogen production, in view of its uncertain environmental impacts and associated climate change risks [23–25].

Synthesising the main findings leads to the following conclusion: *in the context of hydrogen homes, implementing a blue hydrogen production pathway presents a greater social acceptance risk factor than a green pathway*. Foreseeably, this finding may correspond to the broader context of national hydrogen economies, as reflected in recent studies [13,21]. While blue hydrogen is likely a necessity for achieving industrial decarbonisation [26], and may underpin the foundations of developing a national hydrogen economy, qualitative and quantitative results reflect the need to deliver a clear and direct communication campaign to the public.

Addressing misconceptions in the public sphere, which entails an important role for energy representatives, politicians, and media outlets, is crucial to legitimising emerging production pathways for developing a national hydrogen economy. Policy makers and key stakeholders should seek to leverage prospects for better packaging the synergistic effects of scaling up different hydrogen production methods. Critically, ‘multi-regime interactions’ [27,28] between the gas industry and the renewable energy sector could stimulate synergies through symbiosis [29], which promote public trust in the transition [30,31] and support visions for a net-zero society [32]. Therefore, the goal should be on communicating and ensuring complementarity over competition in realising the hydrogen economy [33].

Recasting the twin track approach and justifying the role of blue hydrogen to the public present important starting points for facilitating social acceptance. In doing so, the government can take strides towards building knowledge and awareness of hydrogen across society and supporting social trust in the hydrogen economy. A key recommendation of this report, which may serve as a stepping-stone to raising

acceptance prospects for domestic hydrogen, lies with dispensing with the notion of a ‘twin-track’ production approach, in view of its propensity for raising confusion, doubts and scepticism among the public.

Technology Perceptions

Hydrogen boilers

Across the sample, the strongest consumer perception regarding hydrogen boilers corresponded to an expectation for higher energy efficiency compared to natural gas boilers (*M* = 7.83, *SD* = 2.43). Next, respondents anticipated a comparatively smarter heating system (*M* = 7.33, *SD* = 2.51), followed by a higher level of thermal comfort (*M* = 6.69, *SD* = 2.45). By contrast, there was somewhat less expectation that a hydrogen boiler would be easier to operate (*M* = 6.33, *SD* = 2.59) or require less maintenance and serving (*M* = 6.30, *SD* = 2.76). As a result, consumer confidence in the efficiency and smart performance of hydrogen boilers is higher compared to perceived ease-of-use and effort expectancy.

At the sub-group level, the VEG had the most positive expectation for hydrogen boilers across the five measurements (*M* = 7.32, *SD* = 0.75), followed by the FSG (*M* = 6.99, *SD* = 0.55), the MEG (*M* = 6.86, *SD* = 0.67) and the BLG (*M* = 6.67, *SD* = 0.71). Critically, the results suggest that fuel stressed respondents are more likely to have positive expectations for hydrogen boilers compared to all other sub-groups, excluding the VEG.

This observation corresponds with statements recorded during online focus groups, wherein fuel poor respondents expressed the need for technology upgrades in view of inefficient performing gas boilers and looked somewhat optimistically towards the prospect of hydrogen heating [34]. Relatedly, the extent to which the VEG held the most positive outlook towards hydrogen boilers is highlighted by an extremely strong expectation for a more energy efficient technology (*M* = 8.29, *SD* = 2.09).

Finally, it should be noted that evaluations regarding maintenance and servicing requirements had the lowest variance across sub-groups (*SD* = 0.21), while expectation for a higher level of thermal comfort showed the highest level of variance (*SD* = 0.42), with the remaining measurement items proving equivalent to another (*SD* = 0.28–0.29). It follows that consumers have similar expectations regarding potential maintenance requirements associated with hydrogen boilers, whereas the potential

impact on thermal comfort is perceived somewhat more divergently. The finding infers a likely difference in consumer perceptions regarding more general implications as compared to technical impacts, as observed across the respective sub-groups (see Fig. I-6).

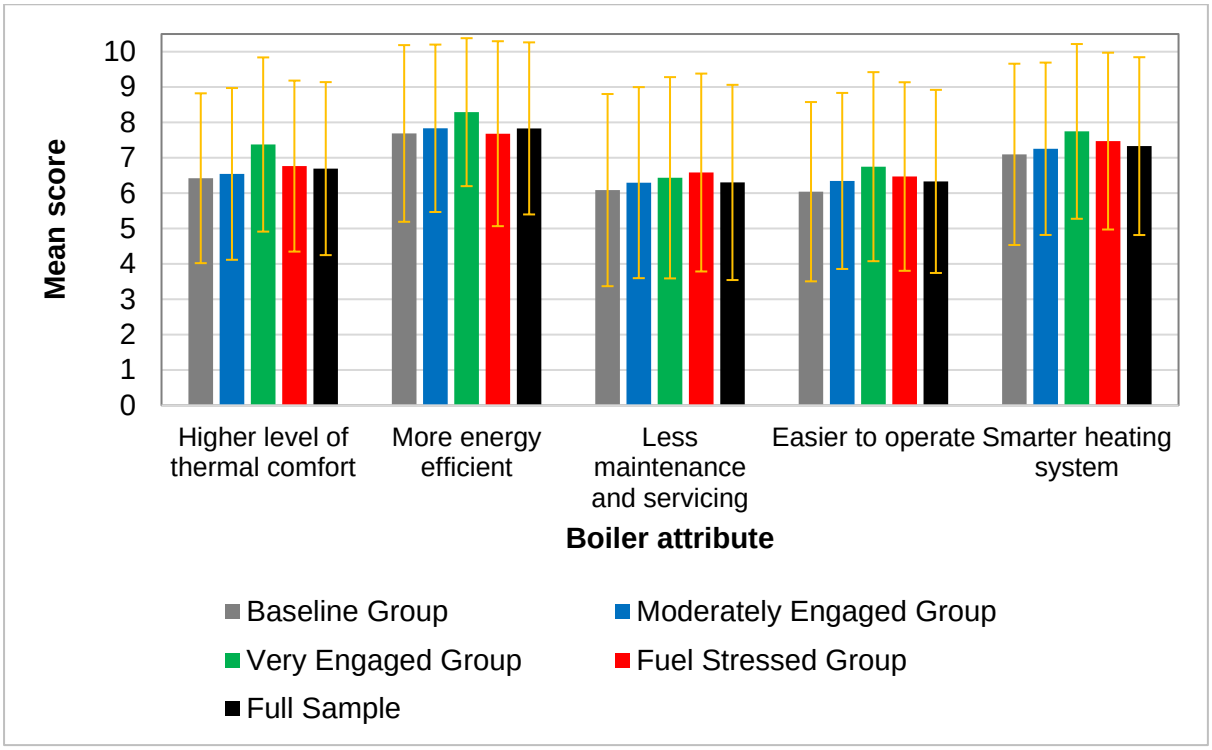


Fig. I-6. Perceptions of hydrogen boiler attributes across the sample and by sub-groups.

Hydrogen hobs

Aligning with the findings on hydrogen boilers, the strongest consumer perception across the sample corresponded to an expectation for higher energy efficiency from a hydrogen hob compared to a natural gas hob (*M* = 6.75, *SD* = 2,40). Next, respondents anticipated a smarter cooking system (*M* = 6.32, *SD* = 2.38), which also mirrors the results for hydrogen boilers. However, there was comparatively less expectation that a hydrogen hob would offer a more modern and sleeker look (*M* = 6.11, *SD* = 2.44), or prove easier to maintain or clean (*M* = 5.91, *SD* = 2.45), while respondents had least expectancy for better cooking control (*M* = 5.85, *SD* = 2.32).

In terms of group-specific differences, the VEG also presented the most positive attitude towards hydrogen hobs across all metrics (*M* = 6.77, *SD* = 0.35), followed by the MEG (*M* = 6.20, *SD* = 0.36), the FSG (*M* = 6.15, *SD*= 0.33) and the BLG (*M* = 5.91, *SD* = 0.40). The results provide further evidence that technology and environmental

engagement are associated with positive perceptions of hydrogen appliances, while fuel stress also presented a positive association when compared to a control group.

Lastly, it emerges that consumer sub-groups have more divergent views when considering whether hydrogen hobs will offer better cooking control (*SD* = 0.44). By contrast, there is a higher degree of convergence in relation to expecting a smarter cooking system (*SD* = 0.30), with the remaining measurement items having similar levels of inter-group variance (*SD* = 0.34–0.38). While the observed differences are somewhat less pronounced as compared to evaluations of hydrogen boilers, it is nevertheless noteworthy that consumers have more divergent perceptions when considering cooking control. One probable explanation is that information provision regarding the flame characteristics of hydrogen cooking is understood differently among consumers (see Fig. I-7). Fig. I-8 compares perceptions of boiler and hob attributes across the full sample to emphasise underlying preference for the former appliance.

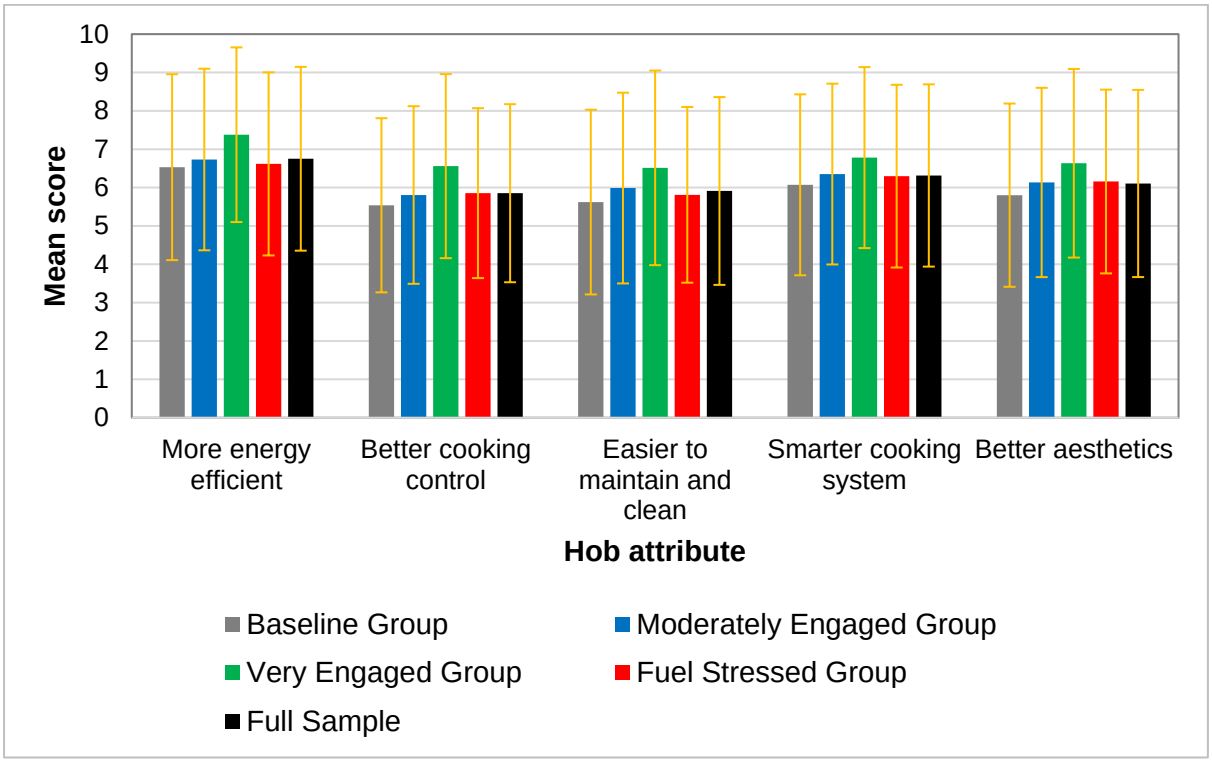


Fig. I-7. Perceptions of hydrogen hob attributes across the sample and by sub-groups.

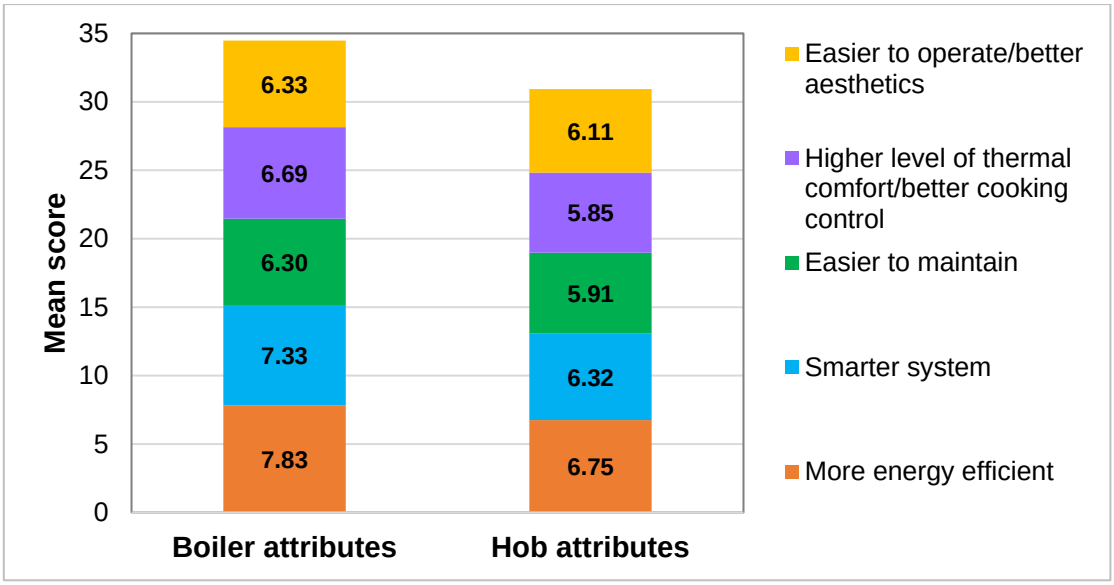


Fig. I-8. Comparison between consumer perceptions of boiler and hob attributes.

Financial Perceptions

Having gauged consumer perceptions regarding the technology attributes of hydrogen appliances, the next question examined financial perceptions through a comparative assessment. Respondents were asked to evaluate their expectation for the price of a hydrogen boiler and hydrogen hob compared to natural gas appliances, in addition comparing potential energy bills for hydrogen to natural gas. All questions were measured on a five-point Likert scale ranging from the least negative answer response (1 = *I expect 'X' to be significantly cheaper*) to the most negative option (5 = *I expect 'X' to be significantly more expensive*).

When considering all measurements across the sample, respondents perceived hydrogen to be at least the same price as current costs for natural gas, if not slightly more expensive (M = 3.72, SD = 0.50). However, there was notable divergence between expectations for hydrogen energy bills (M = 3.14, SD = 1.18) and purchasing costs, which were perceived to be comparably more expensive for both hydrogen boilers (M = 4.04, SD = 1.01) and hydrogen hobs (M = 3.99, SD = 0.97), as shown in Fig. I-9.

This is an important insight as it conveys that while manufacturers have announced a 'price promise' on hydrogen boilers [35], the public may be sceptical of cost parity being delivered. Notably, focus group participants expected hydrogen home appliances to be cost equivalent (N = 10) or more expensive (N = 7), with a minority anticipating a reduction in price (N = 4) [31].

Meanwhile, the survey results highlight an underlying expectation that converting to a hydrogen home would have minimal impact on energy bills. Notably, research conducted in Wales has cautioned that public resistance is likely to ensue if domestic hydrogen leads to an increase in energy costs [36], while a minority of focus group participants also expressed their unwillingness to pay for higher energy bills [31].[7] However, the wider majority anticipated running costs would either the same [31], which aligns to the online survey results.

At the sub-group level, it is noteworthy that fuel stressed respondents have the least negative perception of hydrogen energy bills (M = 3.04, SD = 1.17) and share the least negative financial perception overall (M = 3.62, SD = 0.51) alongside the VEG (M = 3.61, SD = 0.39). By contrast, the BLG has the most negative financial expectation (M = 3.85, SD = 0.56) followed by the MEG (M = 3.70, SD = 0.51). As a result, in terms of financial perceptions, statistically significant differences are observed between the BLG and all other sub-groups,[8] whereas no difference is detected between the remaining groups (i.e. MEG and VEG, MEG and FSG, VEG and FSG,

Critically, based on qualitative responses, *financial risks* associated with the purchasing and running of hydrogen appliances was the third most significant predictor of differences between sub-groups (behind *environmental benefits* and *knowledge deficit*): H (3, N = 1064) = 25.620, ρ<0.001. Notably, concerns were most prevalent along the BLG (Md = 563), followed closely by the FSG (Md = 548), whereas concerns were less pronounced among the VEG (Md = 486), and to a lesser extent, the MEG (Md = 514). As a result, statistically significant differences are observed between the following groups: BLG and MEG; BLG and VEG; FSG and VEG.

[7] Furthermore, following an online survey conducted in the North of England (representative of the HyDeploy2 trial areas), Scott and Powells [17] reported that around two-thirds of respondents (N = 700) were unable to absorb potentially higher prices for hydrogen, even if they expressed willingness to pay more for it.

[8] BLG–MEG: p < 0.001, r = 0.10; BLG–VEG: p < 0.001, r = 0.14, BLG–FSG, p < 0.001, r = 01.3.

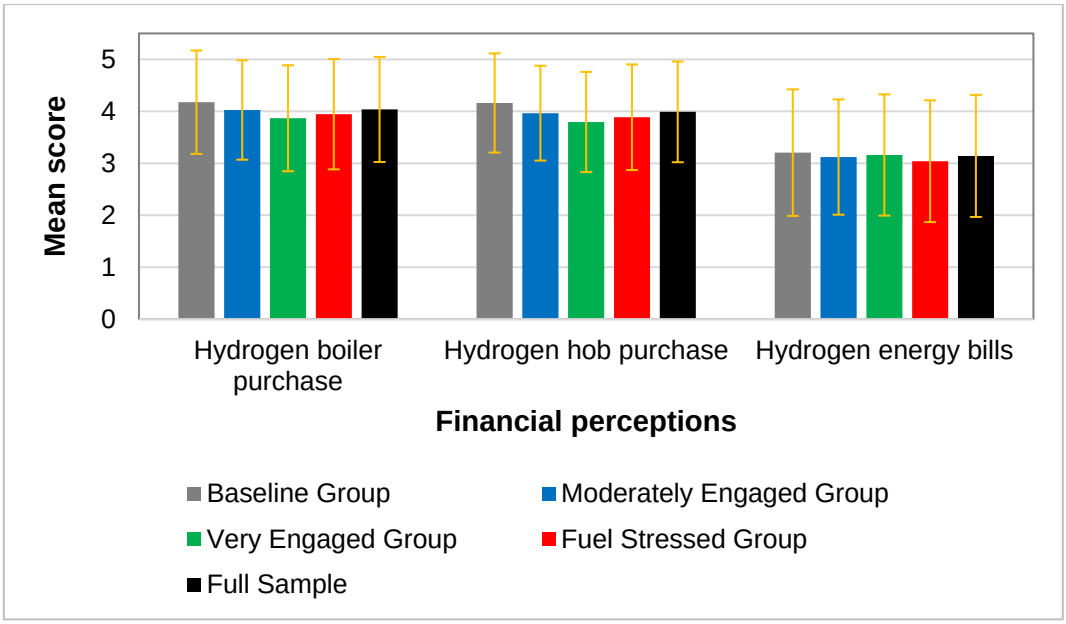


Fig. I-9. Financial perceptions across the sample and by sub-groups.

Safety Perceptions

The second half of the online survey[9] commenced with a series of questions on hydrogen safety. Answers were measured on a scale of 0–10 to reflect safety perceptions of hydrogen compared to natural gas, corresponding to less safe, equivalent, or more safe. Four specific aspects were examined, namely, hydrogen boilers, hydrogen hobs, hydrogen pipelines and underground storage of hydrogen gas, as illustrated in Fig. I-10. Additionally, respondents were asked the following question: How do you perceive the safety *level of hydrogen compared to natural gas in terms of production, storage, transportation and domestic use*?

Survey respondents perceived hydrogen to be slightly safer than natural gas, as reflected by responses to the final question (M = 5.96, SD = 1.94) and across all five measurements (M = 5.86). In terms of the five metrics assessed, a similar level of variance was observed between sub-groups (SD = 0.43–0.47), suggesting that different consumer segments have broadly comparable safety perceptions. Furthermore, within groups, there was minimal variance in terms of how respondents evaluated each safety aspect (SD = 0.09–0.15). Taken together, the results imply that

[9] Upon completing the previous question block on financial perceptions, respondents viewed the following message: "**Well done! You have passed the half-way mark. Thanks for completing the rest of the survey!**"

the688rowthc is likely to hold a broadly uniform view when assessing different aspects of the hydrogen economy in terms of safety.

While safety perceptions proved more homogenous compared to factors such as environmental perceptions and technology perceptions, group-specific differences were nevertheless observed. The VEG expressed the most positive safety perception (*M* = 6.59), followed by the MEG (*M* = 5.87), the FSG (*M* = 5.75) and the BLG (*M* = 5.55). As a result, the largest statistically significant difference corresponded to the BLG and MEG ($p < 0.001$, $r = 0.29$).

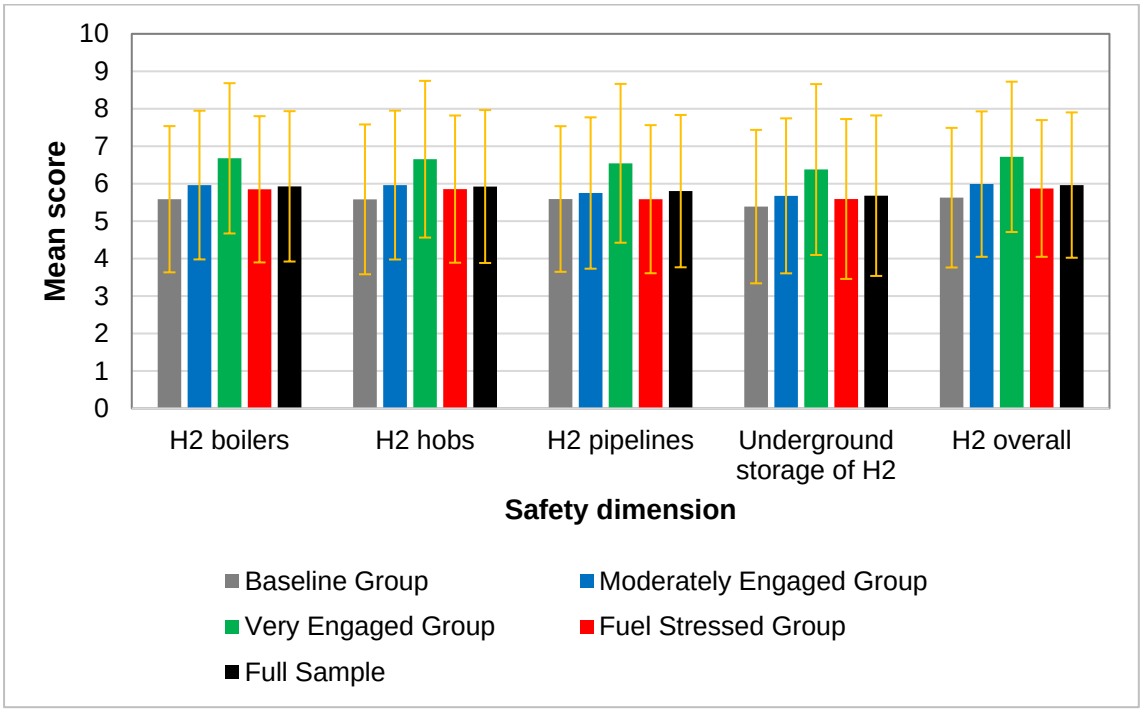


Fig. I-10. Safety perceptions across the sample and by sub-groups.

In terms of written responses referring to hydrogen safety, a different pattern emerged from the data. Overall, safety corresponded to a mid-level or 'secondary' acceptance factor, which presented a largely negative composition as depicted in Fig. I-11. While a proportion of respondents expressed a neutral viewpoint – 688rowth688ing688ed by an expression of contingency on the safety implications of hydrogen or having more information to form their judgement – safety risks associated with hydrogen were cited over four times more frequently than safety benefits. From the 62 references to safety concerns, around half concentrated on particular risk perceptions, with most respondents describing hydrogen as *dangerous*, while some specified these dangers in terms of *explosions* and *high* flammability, as illustrated in Fig. I-12.

These observations are critical in highlighting divergence between how consumers may rate or quantify hydrogen safety when compared to natural gas, and the way hydrogen is likely to be framed or described by the public. The negative framing largely reflects the extant narrative concerning technical barriers to implementation [37–39], and strongly aligns to current representations of hydrogen in the national media [40,41].

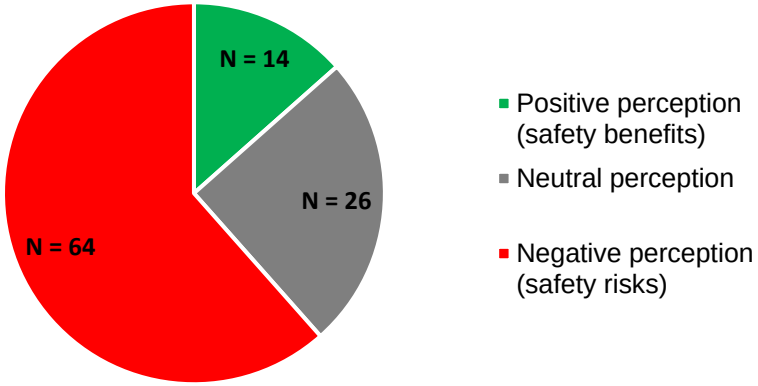


Fig. I-11. Safety perceptions of hydrogen based on qualitative responses.

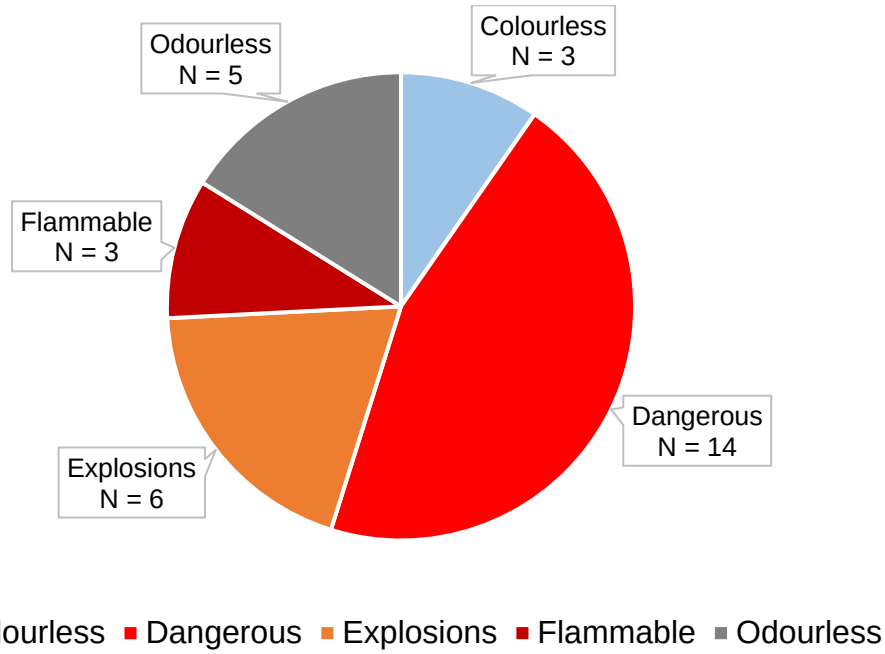


Fig. I-12. Responses citing specific risk perceptions around hydrogen safety.

Perceived benefits

A critical aspect of assessing public perceptions of an emerging technology such as hydrogen home appliances lies with evaluating perceived community benefits [42,43]. In the Australian context, Ashworth [44] defined community benefits related to the hydrogen economy in terms of job security, energy security and environmental improvements, while economic, social, and environmental benefits have been outlined strongly in the UK context [19,45].

Accordingly, respondents were asked to evaluate their expectations for economic, social, and environmental benefits[10], as measured on a scale of 0–10 (i.e. low to high expectation). Across the sample, perceived environmental benefits ranked highest (M = 7.02, SD = 2.07), while economic benefits (M = 6.28, SD = 2.02) and social benefits (M = 6.23, SD = 2.13) were viewed comparably. The results highlight a clear distinction between the extent to which consumers anticipate potential environmental benefits compared to socio-economic benefits, as illustrated in Fig. I-13.

Qualitative responses validated this finding, since environmental benefits ranked as the foremost positive sub-factor of domestic hydrogen acceptance, with 137 responses making an explicit reference to a distinct benefit[11] such as climate change mitigation or sustainability (see Fig. I-14). Notably, the MEG and VEG accounted for nearly two-thirds of references to environmental benefits, while the BLG and FSG made up the remainder of responses. Moreover, environmental benefits emerged as the strongest predictor of group-specific differences in attitudes towards hydrogen homes, whereby the technology and environmentally engaged groups diverged from the BLG and FSG,[12] which follows intuition.

This divergence is reinforced by the online survey results, which saw the VEG rate environmental benefits highest (M = 7.98, SD = 1.72), followed by the MEG (M = 7.30, 1.91), the FSG (M = 6.66, SD = 2.08) and the BLG (M = 6.57, SD = 2.15). Across all three metrics, the same order was retained (VEG: M = 7.43, SD = 0.47; MEG: M = 6.69, SD = 0.52; FSG: M = 6.28, SD = 0.33; BLG: M = 6.06, SD = 0.44). As a result,

[10] Specified as job opportunities and income security (i.e. economic); reduced levels of energy poverty and improved health (i.e. social); and lower carbon emissions and better air quality (i.e. environmental).
[11] An additional 47 responses made a more general or generic comment about hydrogen being good or better for the environment.
[12] Specifically, statistically significant differences were observed between three pairwise comparisons: BLG and MEG (p < 0.001; BLG and VEG (p < 0.001; and FSG and MEG (p = 0.035).

there is substantial evidence that technology and environmental engagement positively predicts perceptions of community benefits, while fuel stress may also act as a motivating factor.

The key result regarding environmental benefits aligns to findings In the literature, both in the UK and internationally. For example, Scott and Powells [46] reported that support for hydrogen in the North of England increased when participants were briefed about the fuel's potential environmental benefits. Additionally, Bentsen et al. [21] found perceived environmental benefits to be a key predictor of hydrogen acceptance in Norway. Moreover, in a recent analysis, Hoffmann and colleagues [47] demonstrated that German respondents express higher support for green hydrogen when the focus is solely 691rowth691ts of climate protection, as opposed to energy security and climate protection. Results from this online survey draw a similar conclusion, as reported in Gordon et al. [48].

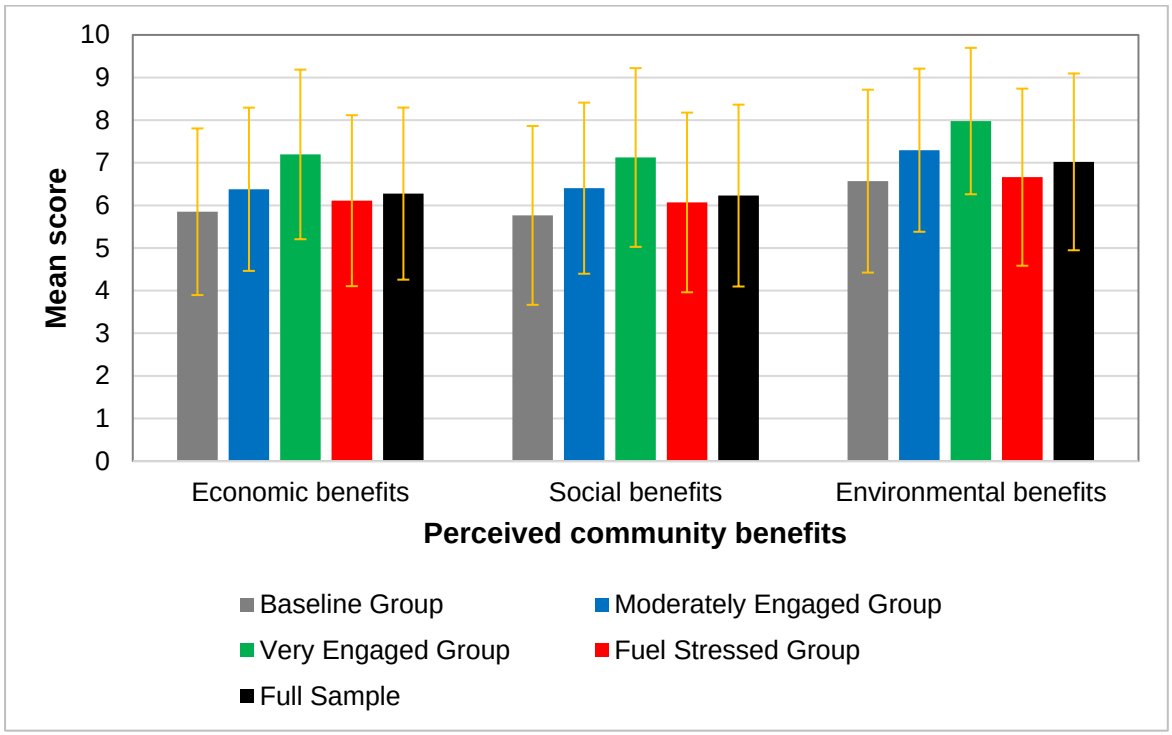


Fig. I-13. Perceptions of community benefits across the sample and by sub-groups.

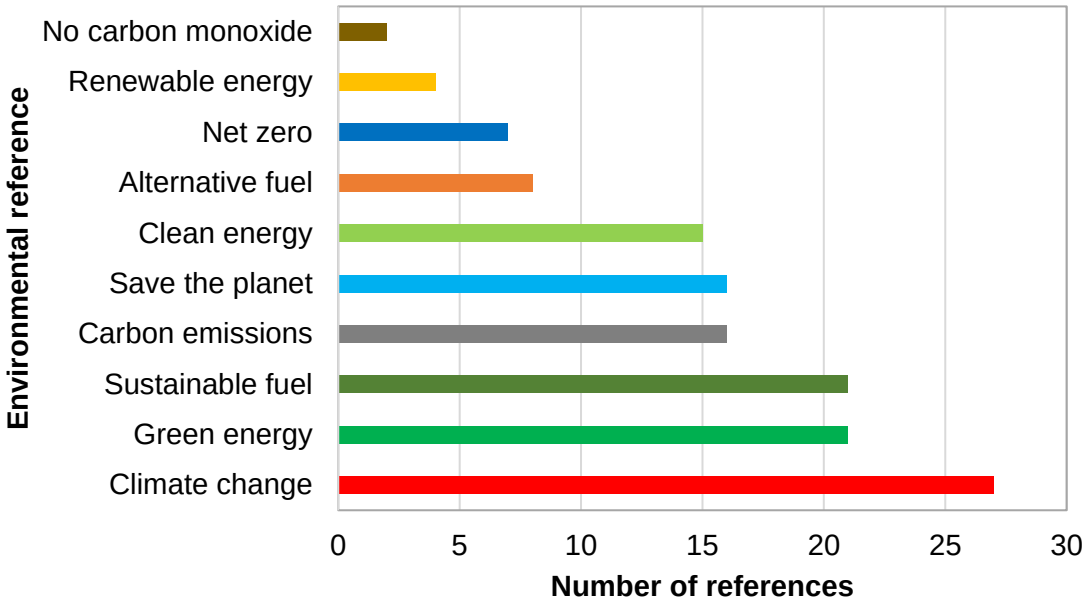


Fig. I-14. Consumer responses citing specific aspects of environmental benefits.

Deployment preferences for hydrogen homes

Community acceptance is a key dimension of transitioning to hydrogen homes [49]. Furthermore, the prospective deployment of hydrogen appliances rests on establishing local trials to enable strategic decision-making [19]. In view of these dynamics, respondents were asked to evaluate three deployment pathways as described in Fig. I-15, as framed by the following question: *To what extent would your attitude towards hydrogen homes be determined by the following scenarios*? Responses were measured on a five-point Likert scale (1 = *No extent*; 5 = *Very significant extent*).

Across the full sample, there was minimal difference in terms of overall preferences (*M* = 3.32, *SD* = 0.06). However, at the sub-group level, responses reflected a somewhat higher level of variance, foremost among the FSG (*SD* = 0.14), while the MEG and VEG were comparable (*SD* = 0.08), with the BLG proving more homogenous in their deployment preference (*SD* = 0.05). Additionally, the BLG attributed most importance to deployment preference (M = 3.40), whereas other sub-groups converged in their overall perspective (MEG: *M* = 3.22; VEG: *M* = 3.20; FSG: *M* = 3.23).

Notably, the BLG attributes more importance to deployment trajectories than other sub-groups, which implies a stronger weighting towards community developments, including a preference for near-term deployment of hydrogen homes. Similarly, and to

a comparatively higher level, the FSG is most in favour of early adoption, while the MEG shares this preference. Interestingly, the VEG places less emphasis on near-term deployment for their local area, instead transmitting above moderate levels of support for deployment within the next 10 years or before 2040. Further investigation of these trends is needed to ascertain whether deployment preferences may be associated with perceptions of other factors such as hydrogen production. For example, it is plausible that trends observed for the VEG imply an underlying assumption that later deployment signifies a green production pathway [48].

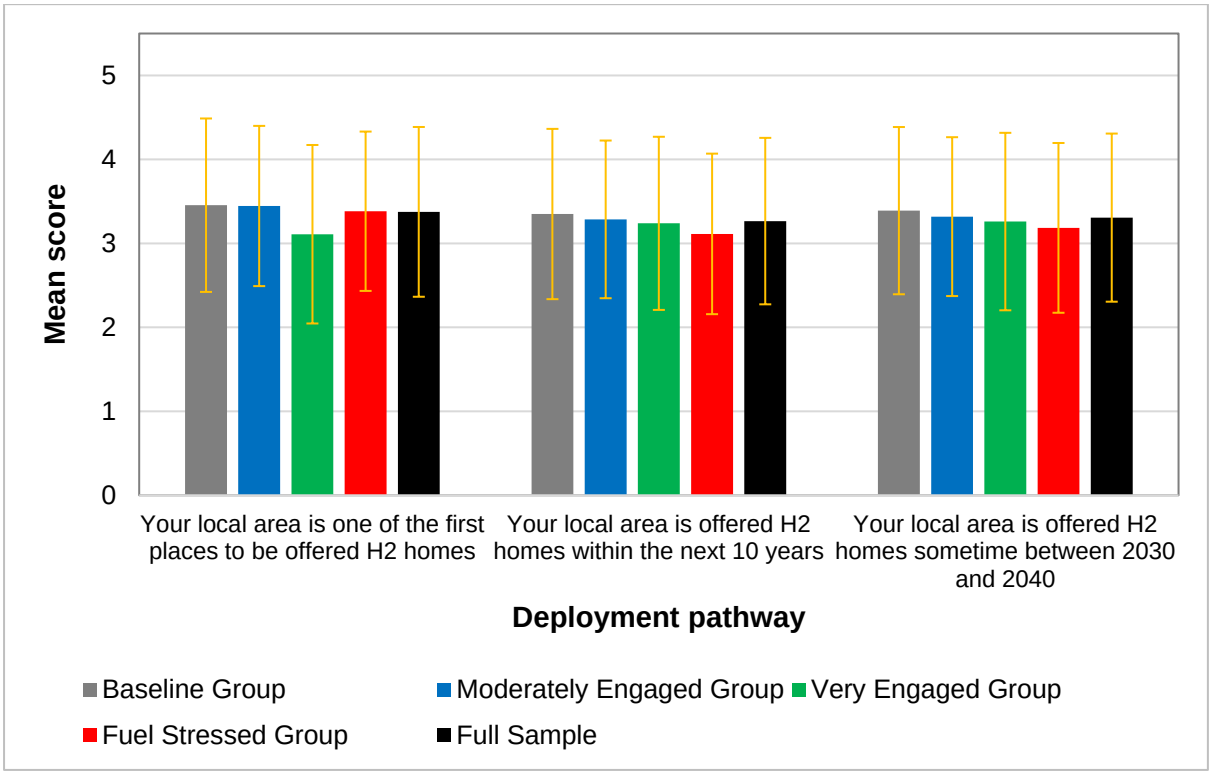


Fig. I-15. Deployment preferences for hydrogen homes across the sample and by sub-groups.

Public Trust

Public trust in the domestic hydrogen transition has been identified is a significant factor in shaping social acceptance, based on both literature review findings [16] and results from online focus groups [31]. Foremost, it has been shown that a lack of trust in the central government and energy sector may create barriers to consumer acceptance [31].

Survey respondents were asked the following question regarding 16 stakeholders with a direct or indirect role in shaping the transition: *How much trust do you have in the*

following stakeholders when it comes to supporting a cost-effective, efficient and fair transition to hydrogen homes? The question was formulated to engage with aspects of competence- and integrity-based trust, as reflected in the energy transitions literature [50–52].

The stakeholders evaluated included the government (i.e. institutional trust), energy sector (i.e. corporate trust), representatives of the gas industry and supply chain (i.e. trust in product quality), and research entities (i.e. trust in research and development). Additionally, four stakeholders were selected to act as proxy for 'social trust', namely, gas distribution network operators (GDNOs), financial institutions, the Office for Gas and Electricity Markets (Ofgem) and the media. The rationale was that each of the four stakeholders should in theory support the public interest, providing a means to gauge levels of social trust in the context of domestic hydrogen.

Across the sample, trust in the government proved lowest (*M* = 4.44), followed by social trust (*M* = 5.06) and trust in the energy sector (*M* = 5.42). By comparison, trust levels related to the dimensions of Product Quality (M = 5.80) and Research & Development (*M* = 5.90) proved comparatively higher, as illustrated in Fig. I-16.

Within each trust dimension, specific patterns further explained the observed trends. On the hand, trust levels in governmental stakeholders (*SD* = 0.40), stakeholders involved in determining the quality of hydrogen home appliances (*SD* = 0.35) and research entities (*SD* = 0.40) proved relatively low. However, comparatively more divergence was reported in relation to the energy sector (*SD* = 0.52) as well as stakeholders composing the dimension of social trust (*SD* = 0.63). Regarding the energy sector, consumers expressed higher levels of trust in renewable energy producers (*M* = 5.82, *SD* = 2.38) compared to fuel/gas supply companies and. Electricity/gas suppliers, as reported in Table I-2. In terms of social trust, the media was perceived as the least trustworthy entity (*M* = 4.03, *SD* = 2.46), comparable to the central government (*M* = 3.97, *SD* = 2.62) at the dimension of institutional trust

At the sub-group level, the VEG expressed the highest level of public trust (*M* = 6.14, *SD* = 0.48), followed by the MEG (*M* = 5.32, *SD* = 0.58), the FSG (*M* = 4.83, *SD* = 0.52) and the BLG (*M* = 4.80, *SD* = 0.53). It is noteworthy that the same trends were observed when considering the dimension of social trust in isolation: VEG: *M* = 5.78, MEG: *M* = 5.03; BLG: *M* = 4.61; FSG: *M* = 4.60. The results highlight the extent to

which stakeholder trust is essentially equal between the BLG and FSG, whereas technology and environmental engagement leads strengthens stakeholder trust in the context of hydrogen homes (see Fig. I-17).

Table I-2. Public trust in stakeholders involved in the domestic hydrogen transition.

Trust dimension	Stakeholder	Mean score (SD)
Government	Central government	3.97 (2.62)
	Regional authorities	4.53 (2.32)
	Local councils	4.74 (2.47)
Energy Sector	Fuel/gas supply companies	4.88 (2.41)
	Electricity/gas suppliers	4.93 (2.45)
	Renewable energy producers	5.82 (2.38)
Product Quality	Trade bodies	5.29 (2.18)
	Boiler manufacturers	5.64 (2.18)
	Gas engineers and technicians	5.99 (2.19)
Research & Development	NGOs	5.24 (2.20)
	Universities	5.956 (2.28)
	Other research institutes	5.91 (2.23)
Social Trust	GDNOs	5.23 (2.38)
	Financial institutions	4.95 (2.37)
	Ofgem	5.47 (2.45)
	Media	4.03 (2.46)

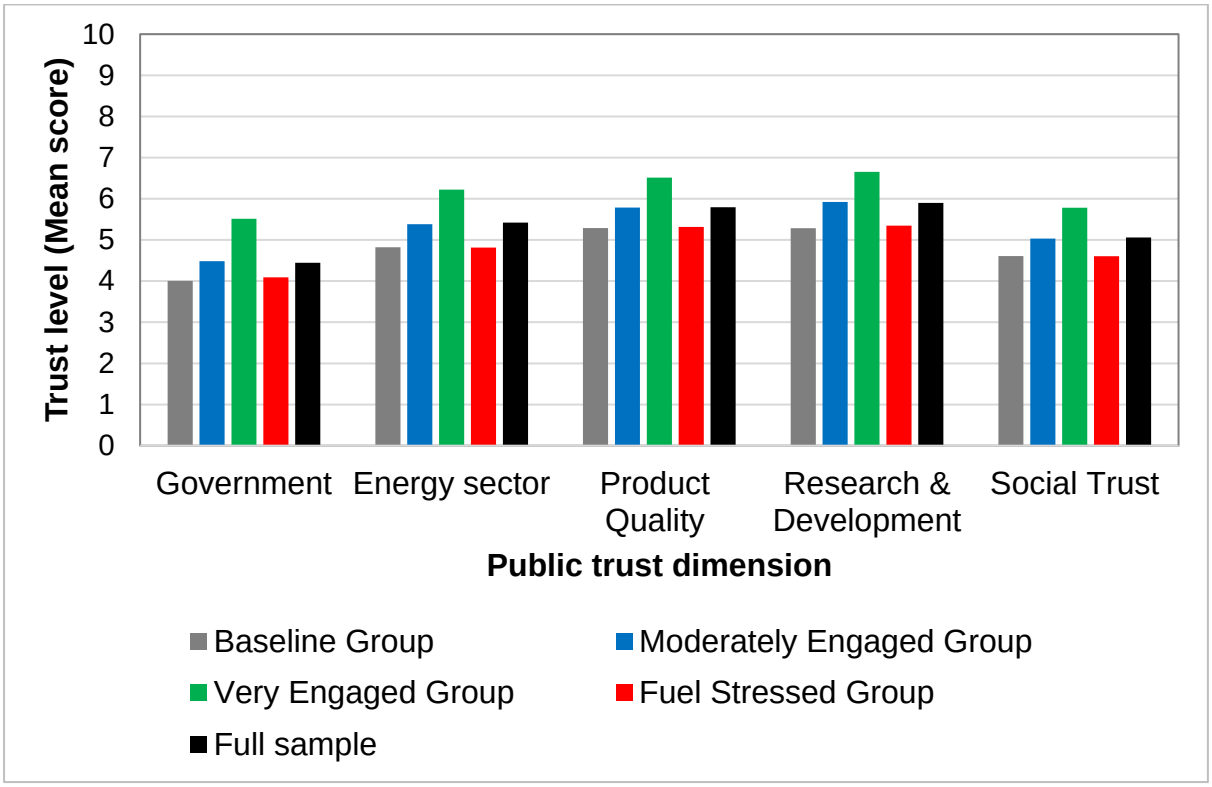


Fig. I-16. Public trust in stakeholder groups across the sample.

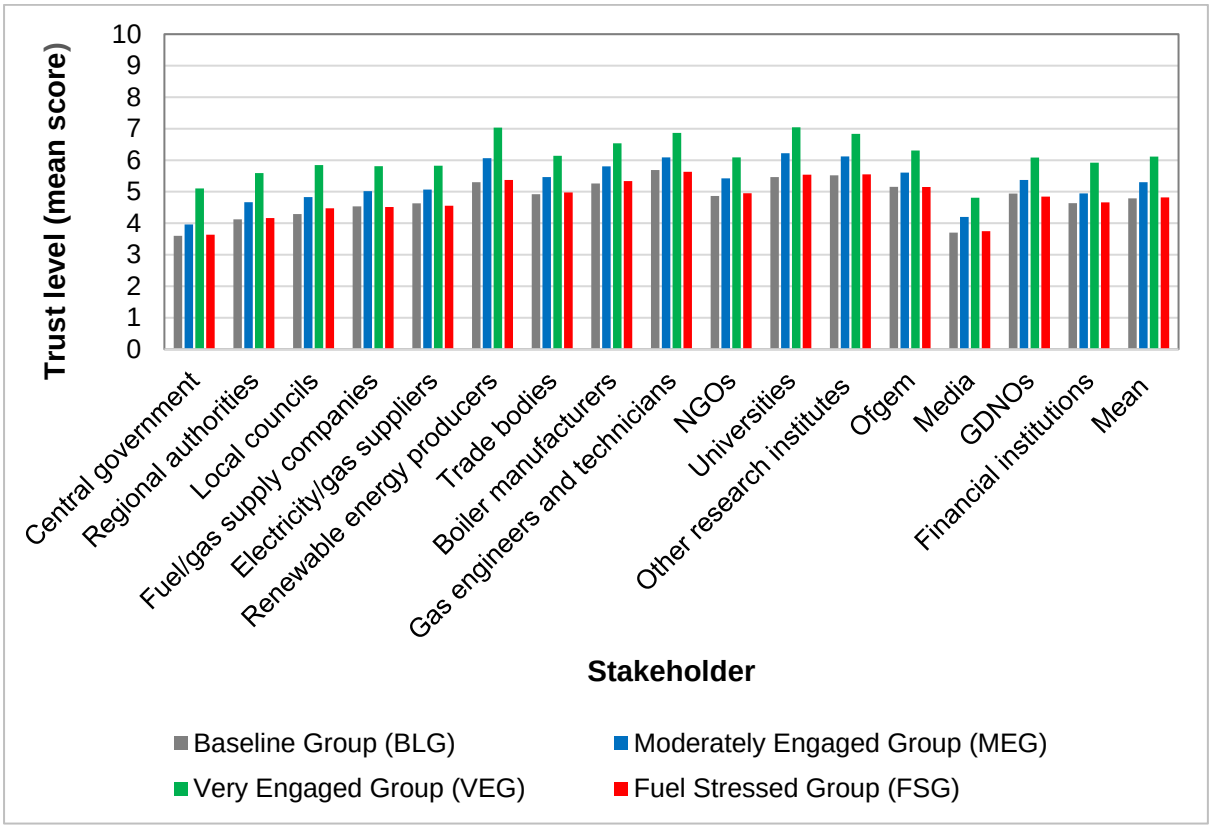


Fig. I-17. Breakdown of trust levels in actors and stakeholders by consumer sub-group.

Priority areas for domestic hydrogen acceptance

At this stage of the survey, respondents were asked a comparative question related to five key aspects of domestic hydrogen acceptance: *How important are the following factors when evaluating your support for hydrogen homes? (i.e. domestic heating and cooking appliances)*? Responses were measured on a five-point Likert scale (1 = *Not important at all*; 5 = *Extremely important*).

The following factors were assessed to support previous areas of examination: cost factors (i.e. purchasing and running costs of hydrogen appliances); safety factors (i.e. safety level of hydrogen heating and cooking); environmental factors (i.e. impacts on air quality and climate change); energy security factors (i.e. reliability of energy supply); and performance factors (i.e. reliability and operation of hydrogen boilers and hobs).

Across the sample, safety proved the most important aspect (M = 4.18, SD = 1.03), followed by performance (M = 3.98, SD = 0.92), energy security (M = 3.90, SD = 0.94), cost (M = 3.86, SD = 1.05) and environmental factors (M = 3.71, SD = 0.98), as

reported in Fig. I-18. The results suggest that safety, technological, economic, and environmental dimensions are respective drivers of domestic hydrogen adoption acceptance, which is a noteworthy observation.

It is logical that safety and technological dimensions would shape the dynamics of domestic hydrogen acceptance, since technology performance and safety levels are critical parameters of energy use in the household environment [17,53], especially when involving gas appliances [54]. The results highlight that the macro- and micro-economic dimensions of domestic hydrogen acceptance may be viewed with near equivalence at this stage of the transition. Finally, when confronted with a comparative choice between potentially critical factors, UK respondents attribute least importance to impacts on air quality and climate change in the context of transitioning to hydrogen homes.

Nevertheless, at the sub-group level, areas of convergence and divergence emerged in relation to the results reported for the full sample (Fig. I-18). Firstly, both the BLG and FSG presented the same rank order for the evaluated factors (i.e. safety, performance, energy security, cost, environmental). Additionally, safety and energy security ranked first and third across all sub-groups. For the MEG, the only change compared to the full sample corresponded to environmental factors ranking fourth and cost factors ranking fifth. Foremost, divergence was detected for the VEG wherein environmental factors ranked second, while performance ranked fourth and costs factors fifth.

The observed differences reinforce how divergent consumer perceptions may be partially attributed to engagement levels in technology and the environment. As a result, the importance of environmental factors was seen to vary most across sub-groups (SD = 0.32), whereas other factors presented relatively low levels of inter-group variance (energy security: SD = 0.12; safety: SD = 0.09; performance: SD = 0.06; cost: SD = 0.04). Within groups, there was also relatively low variance between factors (BLG: SD = 0.25; MEG: SD = 0.17; VEG: SD = 0.14; FSG: SD = 0.20).

Accounting for these dynamics is critically important since the data underlines that none of the five key areas can be overlooked. Nevertheless, there is a stronger imperative to ensure the safety and technological dimension of hydrogen homes meet consumer expectations, while environmental aspects will contribute more significantly

to acceptance among consumers with stronger levels of environmental (and technology) engagement.

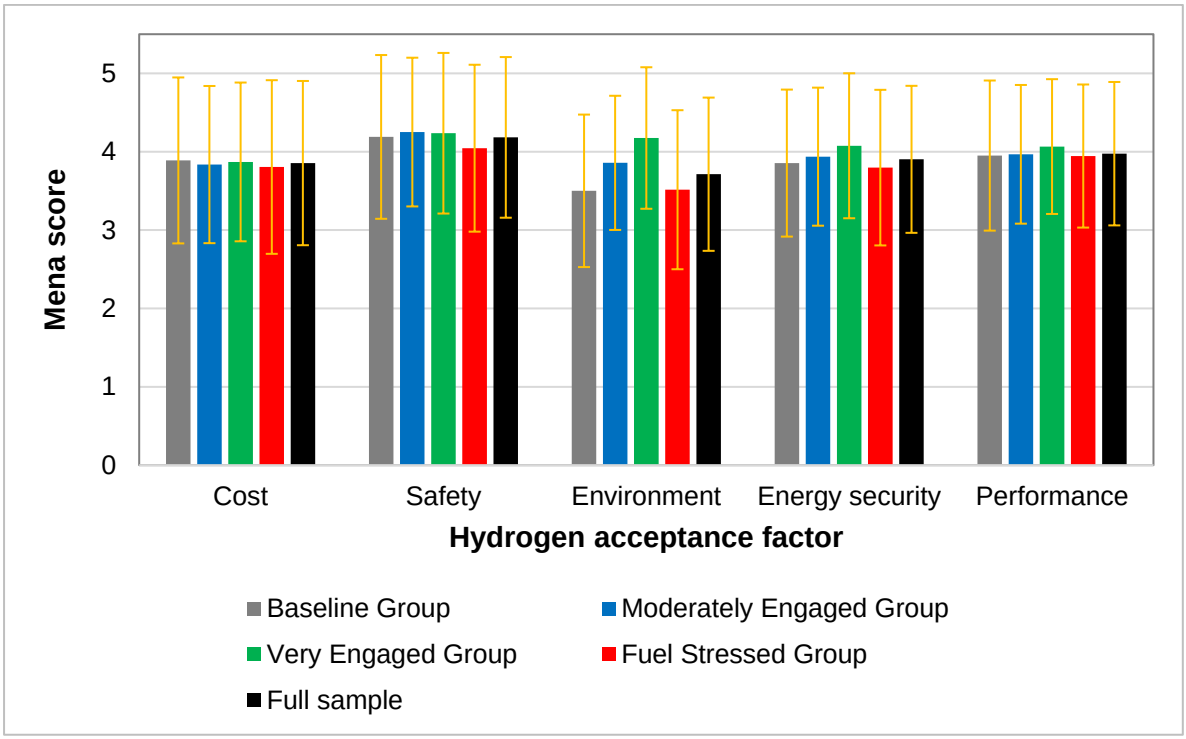


Fig. I-18. Evaluations of hydrogen acceptance factors across the sample and by sub-groups.

Emotional response

Towards the final stages of the online survey, respondents were asked to evaluate their emotional response to domestic hydrogen in view of the following question: *How do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home*? Responses were evaluated on a five-point Likert scale ranging (1 = *No feeling*; 5 = *Very strong feeling*).

As displayed in Fig. I-19 and **Error! Reference source not found.**, positive emotional responses (*M* = 3.05, *SD* = 0.06) exceeded negative emotional responses (*M* = 2.44, *SD* = 0.07), with minimal differences across the measured items. At the sub-group level, optimism was the strongest positive feeling (*M* = 3.21, *SD* = 0.31) while the remaining emotions were near equivalent (*M* = 3.07–3.10, *SD* = 0.27–0.34). In terms of negative emotions, worry emerged as the most prominent feeling (*M* = 2.55, *SD* = 0.13), while other emotions converged closely (*M* = 2.41–2.44, *SD* = 0.11–0.15).

Clear distinctions also emerged between the respective sub-groups. Foremost, the VEG proved the most positive segment by a significant margin (*M* = 3.54). Additionally,

the MEG (*M* = 3.07) and FSG (*M* = 3.03) aligned closely in terms of their positivity, whereas the BLG was the least positive group (*M* = 2.82). The observed differences provide further evidence that technology and environmental engagement, as well as fuel stress, are potential drivers of hydrogen acceptance.

However, at the negative end of the emotional spectrum, somewhat different patterns emerged which are noteworthy within the ongoing context of the energy crisis and cost-of-living crisis [31,55]. Interestingly, the BLG and VEG expressed identical levels of negativity (*M* = 2.41), while the MEG was marginally less negative (*M* = 2.34). However, the FSG proved the most negative sub-group (*M* = 2.64), despite having a parallel positive attitude to an extent. Furthermore, the FSG expressed the highest degree of negativity across all four emotions, suggesting that a mix of fear, worry, unease and pessimism are more prevalent, as opposed to a single emotion in isolation. Nevertheless, the foremost feeling – by a small fraction – was concern, as also observed across the full sample.

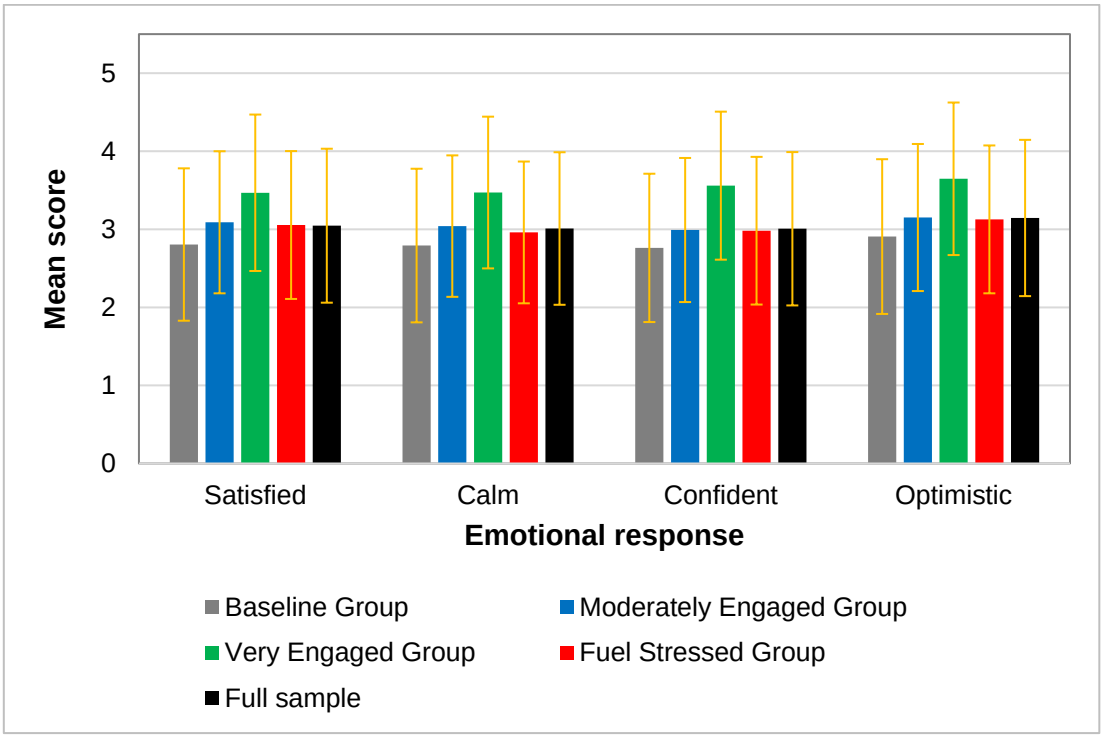
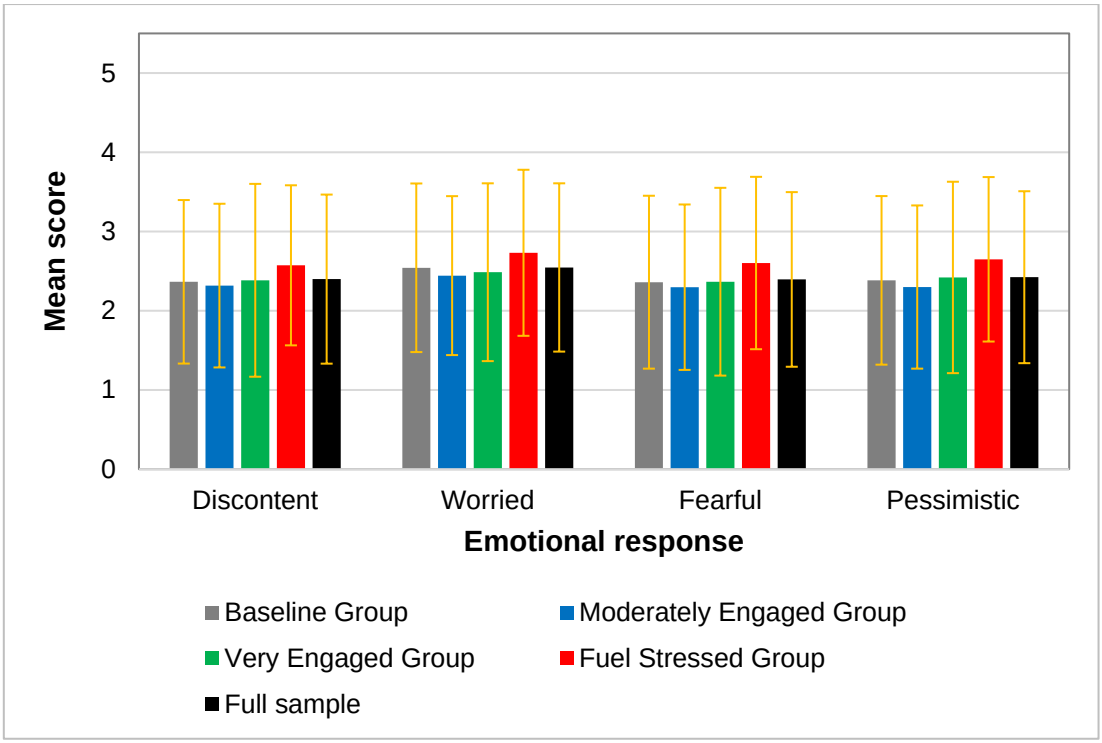


Fig. I-19. Positive emotional responses to hydrogen homes across the sample and by sub-groups.



The results highlight how consumer perceptions of domestic hydrogen exist across a spectrum of potential responses. Based on qualitative responses to the online survey, this spectrum of positive and negative evaluations (see Fig. I-20) has been explored in terms of the 'domestic hydrogen acceptance matrix' [56]. The proposed matrix consists of optimism, hope and curiosity at the positive end, while pessimism, skepticism, and cautiousness compose the negative side, as bridged by a 'hydrogen neutral position' (see Fig. I-21).

The analysis was conducted based on the entirety of consumer statements regarding domestic hydrogen, as opposed to emotional responses alone. Fig. I-20 substantiates that the VEG is the most positive and least negative consumer sub-group, while the BLG is the least positive. Furthermore, the MEG and FSG share the closest distribution of positive, neutral and negative responses among sub-groups. Fig. I-21 provides an additional lens by showing that the VEG is the most optimistic sub-group, while the FSG is the most hopeful and the MEG emerges as the most curious. However, at the negative end of the spectrum, the BLG is the most pessimistic, sceptical, and cautious, which is a critical insight into consumer attitudes towards hydrogen homes.

Both streams of evidence from the online survey highlight that consumer support for hydrogen homes may prove more difficult to secure across the general population, as

compared to consumer segments with a moderate to high level of technology and environmental engagement, or among households experiencing fuel poverty or fuel stress.

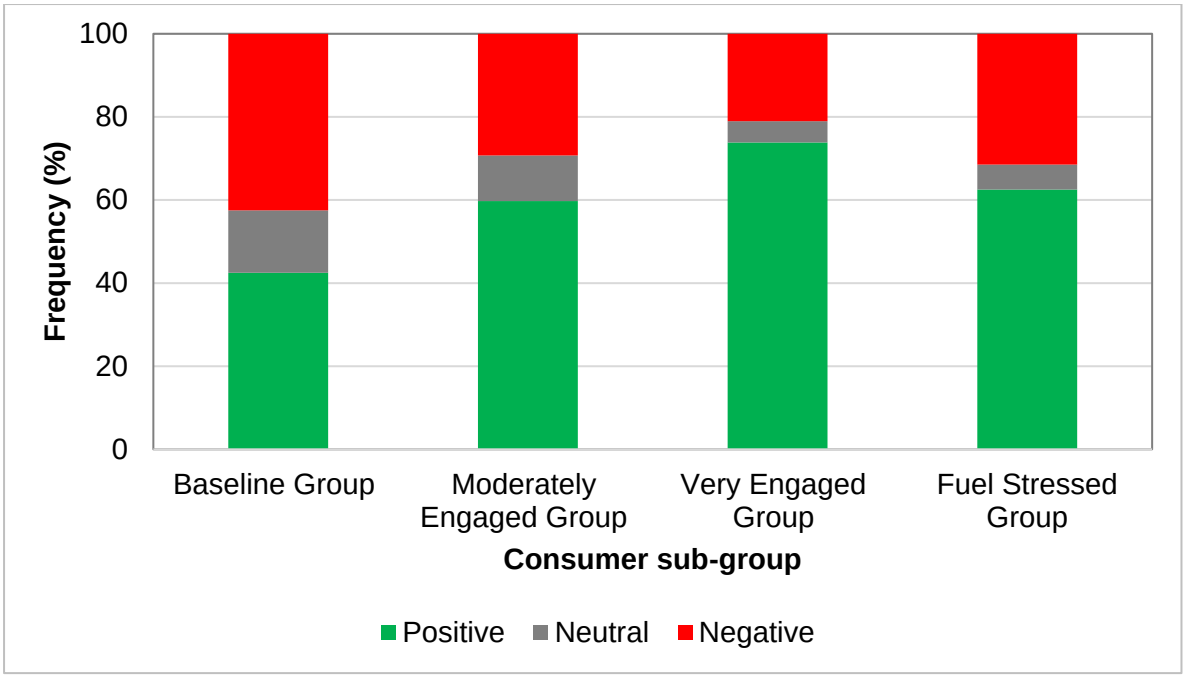


Fig. I-20. Positive, negative and neutral perspectives of domestic hydrogen across sub-groups.

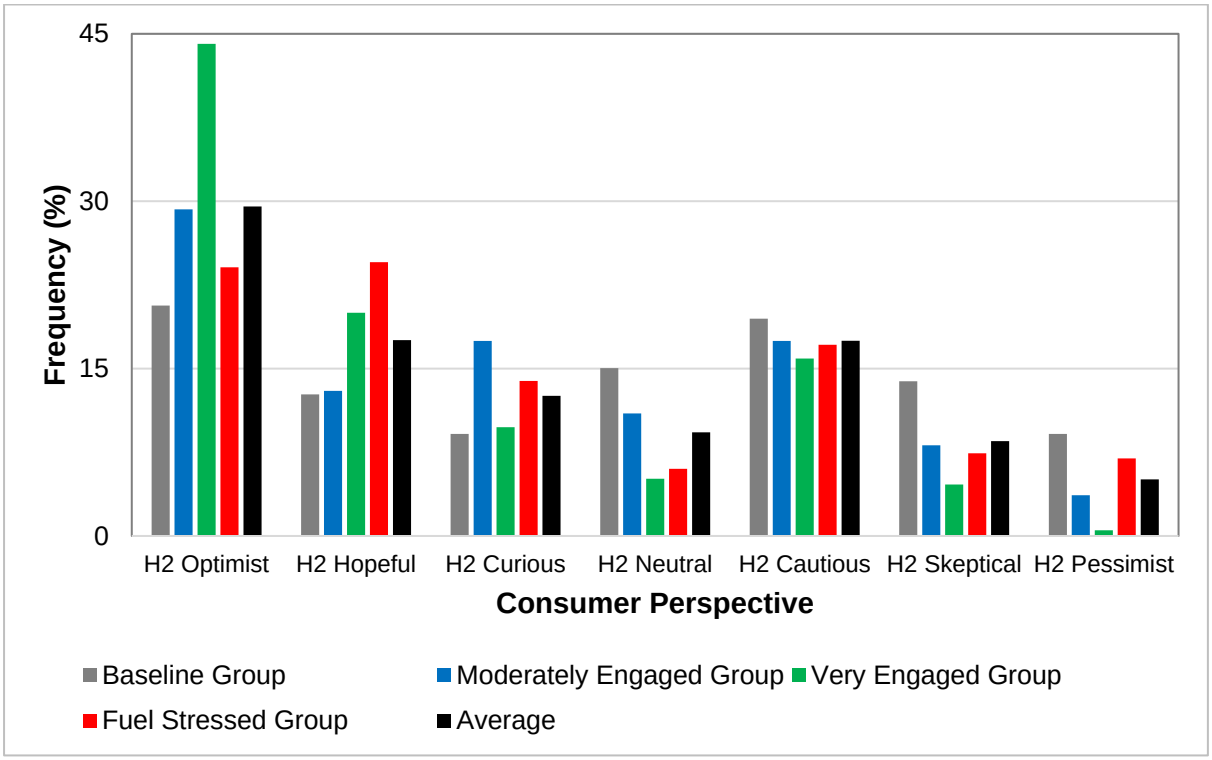


Fig. I-21. Perspectives of domestic hydrogen across sub-groups.

Domestic hydrogen acceptance

The main aim of the survey was to assess domestic hydrogen acceptance, which was achieved by evaluating consumer perceptions towards a range of key areas. To ensure a more direct assessment was also embedded into the survey design, respondents were asked to evaluate their current level of support or opposition for the following: (1) *Hydrogen becoming a critical part of the UK's domestic energy future*; (2) *Hydrogen replacing natural gas in your local area before 2030*; and (3) *Switching your home to both hydrogen heating and hydrogen cooking before 2030*. The rationale was to gauge socio-political, community and household acceptance [49], as measured on a scale of 0 (i.e. opposed) to 10 (i.e. supportive).

Across the full sample, socio-political acceptance proved strongest (M = 6.43, SD = 2.10), followed by household acceptance (M = 6.38, SD = 2.28) and community acceptance (M = 6.34, SD = 2.23), however, there was minimal difference between the three dimensions (SD = 0.04), as represented in Fig. I-22. Across the four consumer sub-groups, there was also minimal difference in terms of the three metrics (BLG: SD = 0.07; MEG: SD = 0.06; VEG: SD = 0.07; FSG: SD = 0.09). It follows that socio-political, community and household acceptance are highly correlated.

While results for the BLG and MEG followed the same rank order as the full sample (i.e. socio-political, household and community acceptance), the VEG expressed more support at the household level, followed by the community and socio-political level, whereas the order was reversed for the FSG. It is noteworthy that high levels of technology and environmental engagement are foremost a driver of support at the individual level. By contrast, fuel stressed respondents are foremost in favour of domestic hydrogen for the country's energy future, but convey less relative support for switching to a hydrogen home in the upcoming years.

Consequently, at the inter-group level, household acceptance corresponded to the most divergent dimension (SD = 0.81), followed by community acceptance (SD = 0.77) and lastly, socio-political acceptance (SD = 0.70). Moreover, there is overwhelming evidence that technology and environmental engagement stimulates a more positive attitude towards domestic hydrogen, which further corroborates prior analysis. The VEG proved the most accepting sub-group (M = 7.52) followed by the MEG (M = 6.66), the FSG (M = 6.06) and the BLG (M = 5.82).

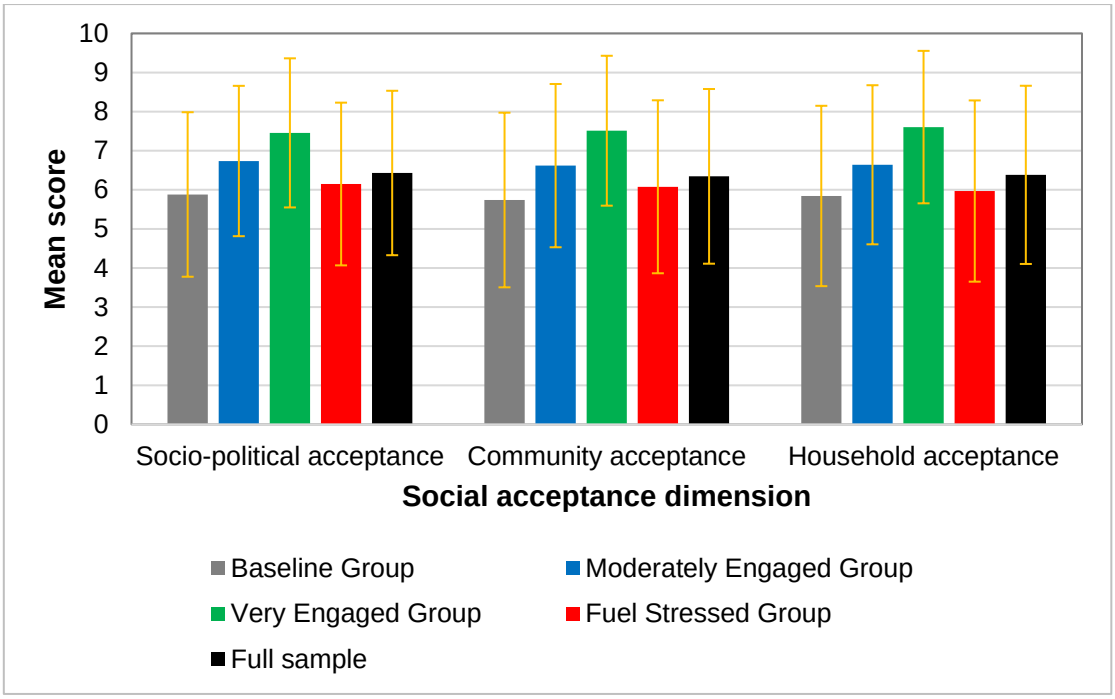


Fig. I-22. Social acceptance of domestic hydrogen across the sample and by sub-groups.

Domestic hydrogen adoption

To support additional insights into the dynamics of household acceptance, respondents were asked three related concerning their willingness to switch to a hydrogen boiler, a hydrogen hob and a hydrogen home before 2030 (i.e. both hydrogen heating and cooking), as measured on a five-point Likert scale (1 = *Not willing at all*; 5 = *Extremely willing*).

Across the sample, respondents proved somewhat willing to adopt hydrogen home appliances before 2030 (*M* = 2.90), with minimal difference between the three options (*SD* = 0.04). However, it is noteworthy that the strongest preference was for a hydrogen boiler (*M* = 2.94, *SD* = 1.00), while a hydrogen home proved the least preferred option (*M* = 2.87, *SD* = 1.04). Furthermore, the same preference was expressed across each consumer sub-group, albeit with minimal variance between the three options (BLG: *SD* = 0.03; MEG: *SD* = 0.02; VEG: *SD* = 0.05; FSG: *SD* = 0.05). At the inter-group level, the same trend was reported (Hydrogen boiler: *M* = 3.02, SD = 0.39; Hydrogen hob: M = 2.97, SD = 0.37; Hydrogen home: M = 2.94, SD = 0.37), further validating the findings and demonstrating the extent to which willingness levels diverged between sub-groups (see Fig. I-23).

The observed pattern is highly noteworthy since online focus group participants expressed significantly higher support for the combined option of a hydrogen home, as reported in Gordon et al. [34]. Additionally, participants expressed their stronger preference for a hydrogen home in terms of convenience, efficiency, 704rowth704ing disruption, and early adoption, among other justifications [34]. Results from the online survey challenge the notion that the combined prospect of switching a hydrogen home is inherently preferable to choosing between hydrogen heating or hydrogen cooking (see Table 7 in [34].

At the sub-group level, the VEG expressed the highest level of willingness to adopt hydrogen home appliances before 2030 (*M* = 3.50, *SD* = 0.05), followed by the MEG (*M* = 2.93, *SD* = 0.02), the FSG (*M* = 2.87, *SD* = 0.05) and the BLG (*M* = 2.62, *SD* = 0.03). This additional finding underscores how strong engagement with technology and environmental issues boosts domestic hydrogen adoption potential, whereas being non-engaged in these areas and non-fuel stressed limits adoption potential. In parallel, it has been shown that fuel stressed citizens (non-engaged in technology and the environment) and consumers with moderate levels of technology and environmental engagement hold similar levels of willingness to adopt domestic hydrogen before 2030.

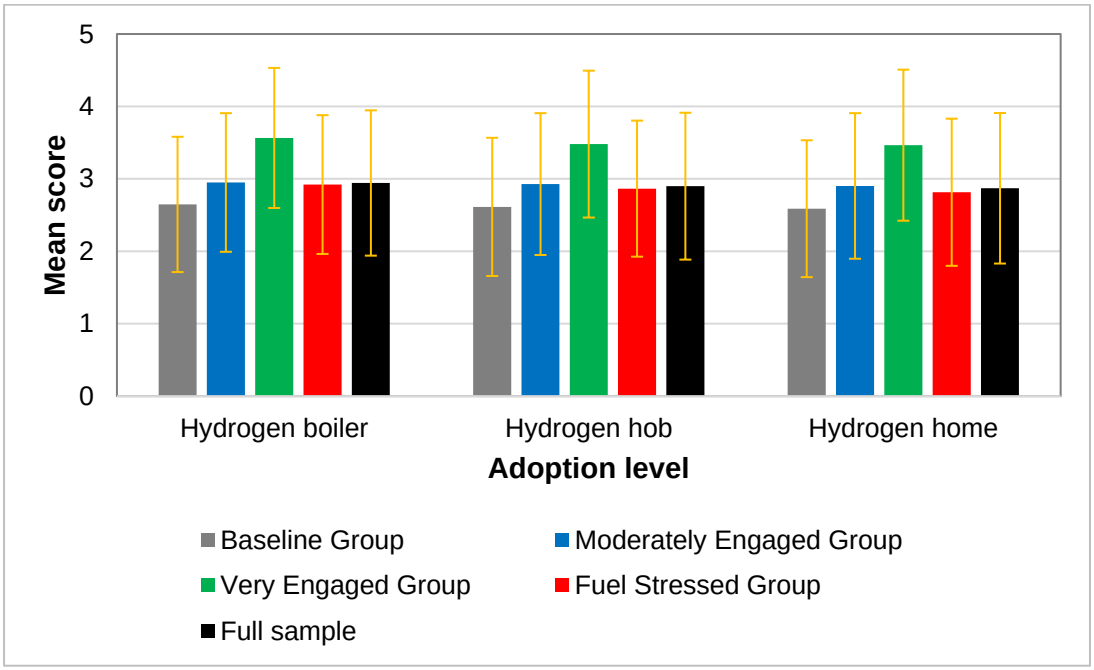


Fig. I-23. Willingness to adopt domestic hydrogen across the sample and by sub-groups.

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APPENDIX J. Results from FIMIX-PLS and PLS-POS

Hair and colleagues [1,2] provide the following guidelines for selecting the correct number of segments finite-mixture partial least squares (FIMIX-PLS):

Information criteria: If AIC3 and CAIC indicate the same number of segments, choose this solution. Alternatively, jointly consider AIC3 and BIC. Also, consider the segment number as indicated by AIC4 and BIC. Generally, choose fewer segments than indicated by AIC and more segments than indicated by MDL5.

Entropy criterion: The normed entropy statistic (EN) uses the observations' segment membership probabilities to indicate whether the partition is reliable or not. The more observations exhibit high segment membership probabilities, the more clear-cut their segment affiliation is. The EN ranges between 0 and 1, with higher values indicating a better-quality partition. Prior research provides evidence that EN values above 0.50 permit a clear-cut classification of data into the pre-determined number of segments.

Segment sizes: Ensure that the segment sizes meet the minimum sample size requirements. If not met, reduce the number of segments or discard the extraneous segments and focus on the remaining larger ones.

To supplement FIMIX-PLS, Becker et al. [3] proposed and developed guidelines for prediction-oriented segmentation (POS-PLS). Applying the methods and following the guidelines in Table J-1 shows that a one-segment solution fits the data best, suggesting the sample data is not characterised by unobserved heterogeneity. Table J-2 shows no segmentation solution wherein the normed entropy statistic is less than 0.50, while results for respective information criterion fail to align consistently. Additionally, Table J-3 and Table J-4 show that a three-segment solution is the upper limit, however, the information criterion results do not support the feasibility of a two- or three-segment solution.

Table J-1. Selected information criteria and their performance in FIMIX-PLS.

Abbreviation	Criterion name	Performance in FIMIX-PLS
AIC	Akaike's information criterion	• Weak performance • Very strong tendency to overestimate the number of segments • Can be used to determine the upper limit of reasonable segmentation solutions
AIC_3	Modified Akaike's information criterion with factor 3	• Fair to good performance • Tends to overestimate the number of segments • Works well in combination with CAIC and BIC
AIC_4	Modified Akaike's information criterion with factor 4	• Good performance • Tends to over- and under-estimate the number of segments
BIC	Bayesian information criterion	• Good performance • Tends to underestimate the number of segments • Should be considered jointly with AIC_3
MLD_5	Minimum description length with factor 5	• Weak performance • Very strong tendency to underestimate the number of segments • Can be used to determine the lower limit of reasonable segment solutions
EN[a]	Normed entropy statistic	• Should exceed 0.50

Source: Reproduced from Hair et al. [1] with addition of Normed entropy statistic.

Table J-2. Fit indices for one-to-five segment solution.

	Number of segments				
	1	2	3	4	5
AIC	3216.417	3093.234	3017.497	2982.136	**2962.925**
AIC_3	3226.417	3114.234	3049.497	3025.136	**3016.925**
AIC_4	3236.417	3135.234	3081.497	**3068.136**	3070.925
BIC	3271.619	3209.159	3194.145	**3219.506**	3261.017
CAIC	3281.619	3230.159	3226.145	**3262.506**	3315.017
MDL5	**3572.429**	3840.859	4156.735	4512.986	4885.388
EN	n/a	**0.218**	**0.244**	**0.373**	**0.416**

Red text highlights norm entropy statistics falling below the guideline of 0.50.

Table J-3. Segmentation solutions in FIMIX-PLS (Percentage and sample size)

Two-segment solution					
Segment1		Segment2			
	0.636	0.364			
	1173	672			
Three-segment solution					
Segment1		Segment2	Segment3		
	0.474	0.264	0.262		
	875	487	483		
Four-segment solution					
Segment1		Segment2	Segment3	Segment4	
	0.449	0.257	0.251	0.043	
	828	474	463	79	
Five-segment solution					
Segment1		Segment2	Segment3	Segment4	Segment5
	0.429	0.247	0.224	0.054	0.046
	792	456	413	100	85

Table J-4. Segmentation solutions in PLS-POS.

Two-segment solution					
	Segment 1	Segment 2			
Number	662	1183			
Three-segment solution					
	Segment 1	Segment 2	Segment 3		
Number	610	547	688		
Four-segment solution					
	Segment 1	Segment 2	Segment 3	Segment 4	
Number	24	529	640	652	
Five-segment solution					
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
Number	26	354	604	321	540

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APPENDIX K. The dynamics of domestic hydrogen adoption: safety, technological, economic and environmental perspectives

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Highlights

- The UK public has a positive perception of hydrogen safety compared to natural gas
- The performance attributes of hydrogen boilers and hobs are perceived favourably
- Consumers have an expressed preference for green over blue hydrogen production
- Macro-economic concerns are more significant than micro-economic factors
- Positive perceptions of hydrogen homes outweigh negative perceptions

Keywords: Hydrogen homes; Importance-performance map analysis; Partial least squares structural equation modelling; Safety perceptions; Social acceptance; Technology Adoption.

Abstract

The UK government is set to take a strategic decision by 2026 on the role of hydrogen in decarbonising homes. While scholars have recently advanced the social science research agenda on hydrogen technology acceptance, studies are yet to engage with the prospective dynamics of adopting hydrogen homes. In response, this study examines the adoption potential of hydrogen heating and cooking technologies, as evaluated through the eyes of consumer. Taking a market acceptance perspective, this research draws on data from a broadly nationally representative online survey to examine the influence of technological, economic, safety, and environmental factors on domestic hydrogen adoption in the UK context. The analysis follows a three-stage empirical approach, integrating findings from descriptive statistics, partial least squares structural equation modelling, and important-performance map analysis to crystallise insights on this emergent subject. Results suggest the environmental credentials of hydrogen production pathways, safety implications of the transition, and performance of hydrogen heating and cooking appliances will prove critical to market adoption, with these factors exhibiting a positive influence. However, macro- and micro-economic factors appear less influential during the formative phase of the transition, wherein the risks associated with energy insecurity and fuel poverty exceed concerns over purchasing and running costs. By bridging the knowledge gap between social acceptance and technology adoption, this contribution reinforces the need for consumer engagement in the hydrogen economy, advocating for more fine-grained analyses of technology acceptance dynamics to support decarbonisation strategies.

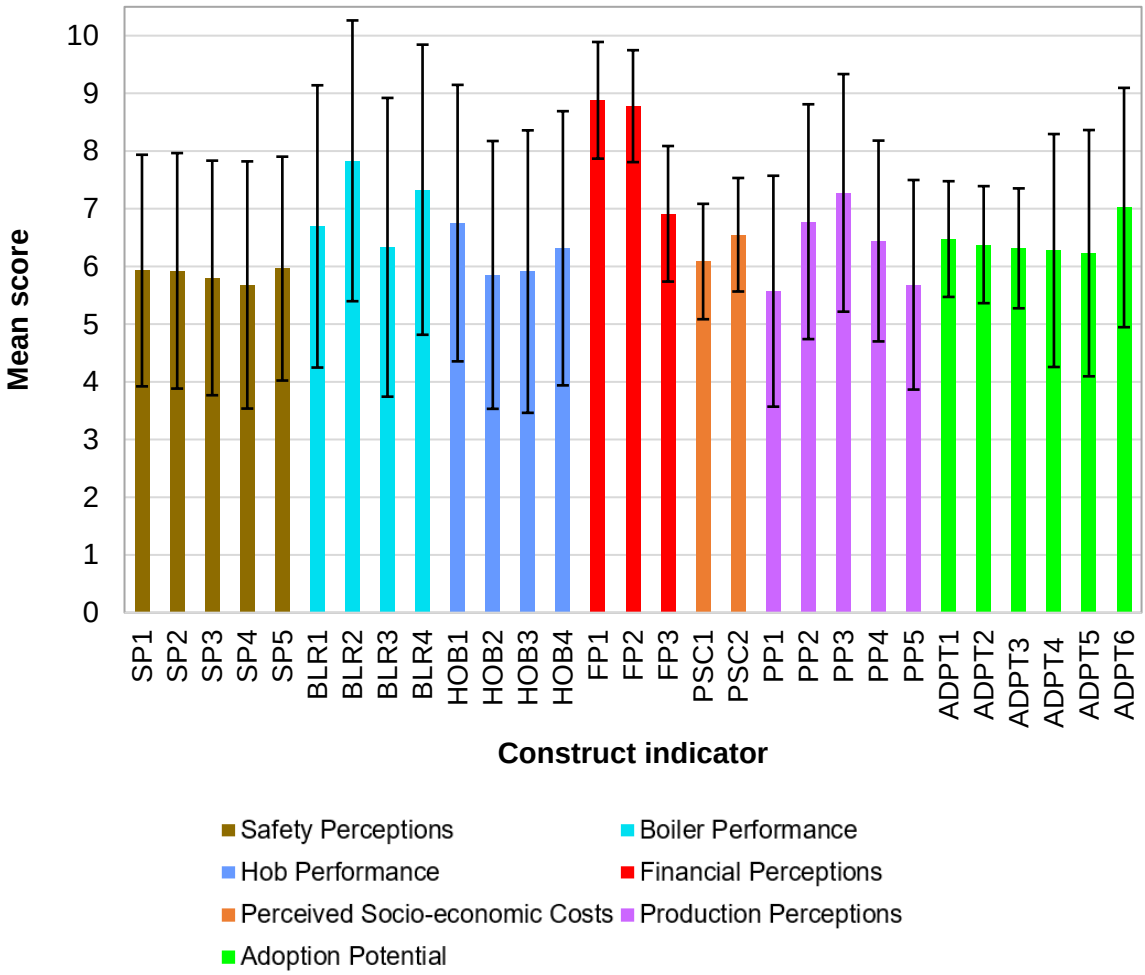

Fig. K-1. Descriptive results for construct indicators.

Table K 1. Assessment of reliability, convergent validity, and multicollinearity.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety Perceptions (SP)	0.918	0.920	0.939	0.754	1.356
Boiler Attributes (BLR)*	0.723	0.729	0.828	0.548	1.663
Hob Attributes (HOB)*	0.852	0.853	0.900	0.693	1.663
Technology Perceptions (TP)**	0.774	0.774	0.898	0.816	1.276
Financial Perceptions (FP)	0.732	0.870	0.821	0.606	1.060
Perceived Socio-economic Costs (PSC)	0.730	0.734	0.881	0.787[b]	1.122
Production Perceptions (PP)	0.816	0.844	0.870	0.578	1.231
Hydrogen Adoption (ADPT)	0.855	0.862	0.889	0.571	n/a

** Higher-order construct
* Lower order constructs
[a] Since PSC has two indicators, the AVE is by default larger than 0.50.

Table K-2. Heterotrait-monotrait results for assessment of discriminant validity.

	BLR	FP	HOB	ADPT	PSC	PP	SP
BLR							
FP	0.199						
HOB	0.803	0.104					
ADPT	0.537	0.273	0.492				
PSC	0.210	0.224	0.183	0.423			
PP	0.298	0.104	0.310	0.616	0.329		
SP	0.441	0.170	0.494	0.585	0.159	0.413	

Table K-3. Results of path analysis and hypothesis testing.

Hypothesis	β coefficient	*t*-statistic	ρ-value	f^2	Result
H1: SP → (+/-) ADPT	0.277	13.045	<0.001	0.121*****	Accepted
H2a: BLR → (+) TP	0.474	62.834	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.631	70.154	<0.001	n/a	Accepted
H2c: TP → (+) ADPT	0.250	10.744	<0.001	0.105*****	Accepted
H3: FP → (-) ADPT	-0.116	6.629	<0.001	0.027*****	Accepted
H4: PSC → (-) ADPT	-0.157	9.230	<0.001	0.047*****	Accepted
H5: PP → (+/-) ADPT	0.324	17.156	<0.001	0.183******	Accepted

****** Moderate effect size.
***** Small effect size.

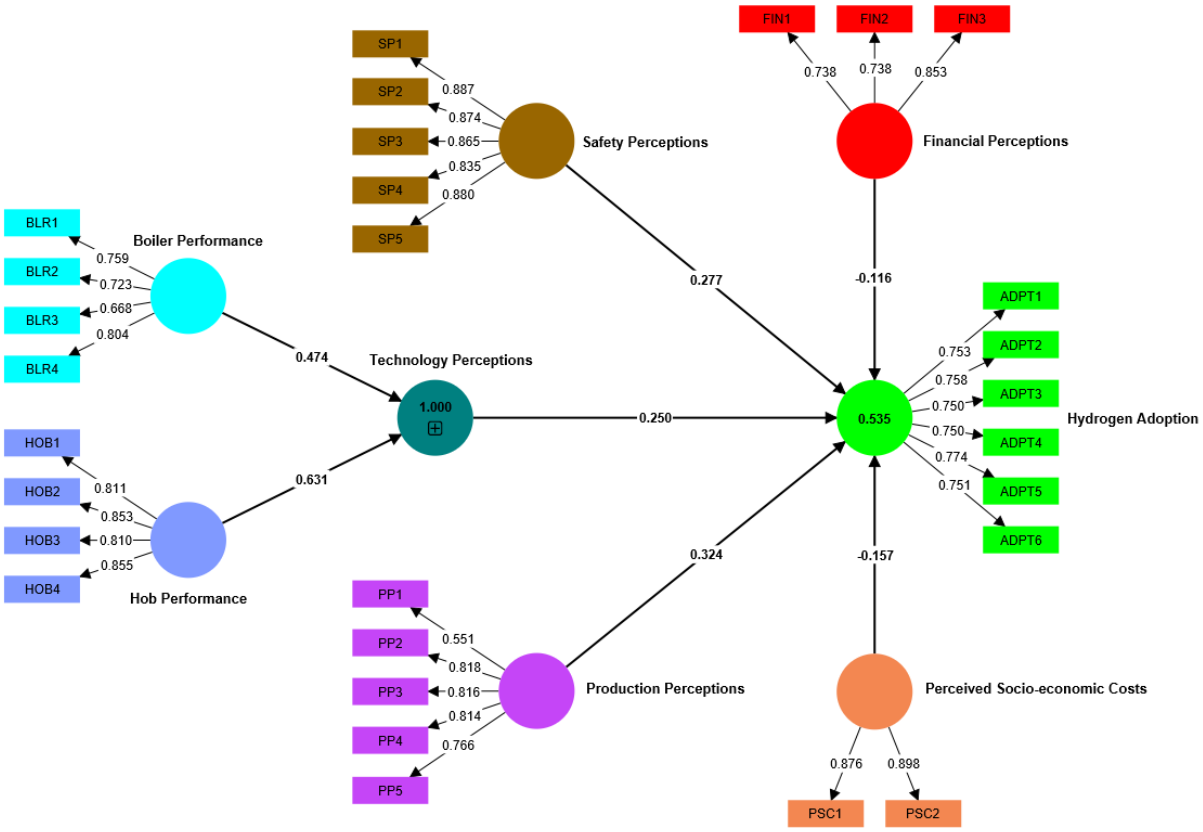

Fig. K-2. Structural model path coefficients.

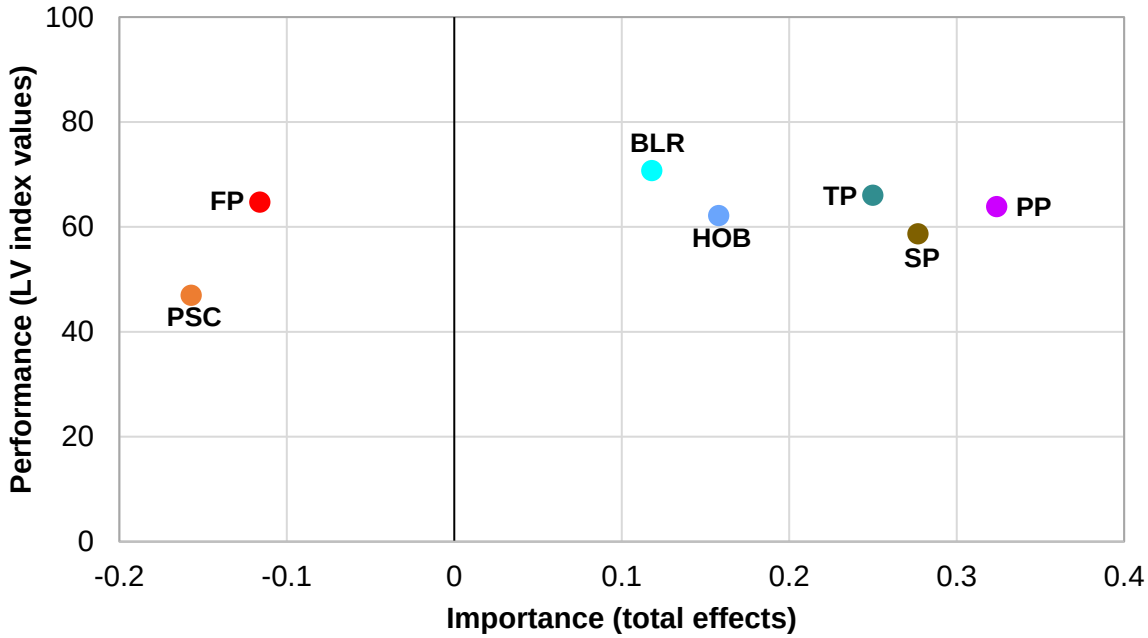

Fig. K-3. Importance-performance map analysis for domestic hydrogen adoption.

Turquoise = Boiler Performance (BLR); Blue = Hob Performance (HOB); Green = Technology Perceptions (TP); Red = Financial Perceptions (FP); Orange = Perceived Socio-economic Costs (PSC); Brown = Safety Perceptions (SP); Purple = Production Perceptions (PP).

APPENDIX L. Towards a unified theory of domestic hydrogen acceptance (chapter 2)

Table L-1 provides details on the results of the systematic literature review (SLR) on hydrogen energy acceptance; reporting the year of the study, whether a theoretical, conceptual, or empirical model was included, the aims and scope, and key findings. Table L-2 reports whether the study was retrieved via SLR or through subsequent snowballing (SB), the technology analysed and corresponding national context(s), methods and theoretical or conceptual foundations, and the number of social acceptance dimensions engaged within the empirical analysis.

Table L-1. Aims and findings for retrieved studies on hydrogen energy acceptance (N = 33).

Study and year	Theoretical, conceptual, or empirical model included	Aims and scope	Key findings on consumer acceptance
[1] 2008	Yes	• Investigates the moderating role of an extreme evaluation of trust and negative affective associations on the inverse relationship between risk and benefit judgements	• A negative evaluation of stakeholder trust was associated with higher perceived risks and lower perceived benefits. • Perceptions of danger associated with hydrogen resulted in higher perceived risks and lower perceived benefits, attributed to the associative mode of processing.
[2] 2010	No	• Evaluates how processes of public understanding and perceptions related to a community-based hydrogen project are generated	• Community concerns outweighed any negative effect related to risk perceptions such as explosiveness and flammability. • The role of emotion in decision-making was associated with a positive response to community-based hydrogen generation and storage.
[3] 2011	Yes	• Examines the factors that impact customer acceptance of hydrogen fuel cell vehicles and tests the relationships among these factors	• Positive perception of the government ‘low carbon, green growth’ policy had little impact on creating positive perceptions of HFCV performance or stimulating purchase intention. • Desire to be regarded as a consumer with environmental concern was positively associated with purchase intention.

[4] 2013	No	• Tests the explanatory value of variables associated with moral considerations (i.e. NAM) and self-interest (i.e. TBP) in relation to acceptance of a local hydrogen fuelling station	• For supporters of a local HFS, the combined NAM-TPB best explained intention to act, however, self-interest was a secondary goal after moral considerations. • Overall, the NAM provided stronger explanatory value than the TPB for both supporters and opponents.
[5] 2014	Yes	• Analyses public perceptions of hydrogen energy technologies (HETs, comparing pooled data from representative surveys conducted in 2008 and 2013	• Public support for HETs declined among the Dutch public, owing to a general decline in trust in science and technology. • Decline in trust in science and technology, and public support for HETs proved more pronounced among the highly educated.
[6] 2014	Yes	• Examines intentions towards performing supporting and protesting actions towards a local hydrogen fuelling station	• For the group of supporters, the most significant predictors (in order of priority) were personal norm, positive affect, perceived effects, and attitude towards the behaviour, while eight other variables were less significant. • For the group of opponents, the most significant predictors were personal norm, negative affect, trust in the industry, and perceived effects, while four other variables were less significant.
[7] 2015	Yes	• Identifies the factors affecting citizens' acceptability levels for the implementation of local hydrogen fuelling station, and tests the relationships between different socio-demographic, spatial, and psychological variables	• Psychological variables explained public acceptability better than socio-demographic and spatial variables, which were mostly fully mediated by the psychological variables. • The strongest predictors were positive affect, negative affect, expected local effects, and expected societal and environmental effects, while the Not-In-My-Back-Yard phenomenon was also observed.
[8] 2016	Yes	• Examines public perceptions of developing a national hydrogen industry and producing green hydrogen	• Respondents expressed a high level of concern about hydrogen safety, but this perception is insignificant on support. • Public belief in the domestic hydrogen industry conforming to international safety standards positively predicted support for hydrogen energy development.
[9] 2017	Yes	• Examines the significant external variables that affect	• Correct product knowledge lowered consumers' uncertainty regarding hydrogen-electric motorcycles and increases their purchase intentions.

		consumers' purchase intentions toward using hydrogen-electric motorcycles	• Consumers' perceived quality and risk influenced purchase intentions through perceived value.
[10] 2017	No	• Characterises risk perception of a local hydrogen fuelling station and analyses public acceptance levels according to socio-psychological variables	• Men were more supportive of a local HFS than women; the former group had an 82% acceptance rate, whereas 48% of women express 'dread', which is the most dominant affective response across the sample. • Overall, risk perceptions factors were better predictors of acceptance than attributes and socio-demographic factors.
[11] 2018	Yes	• Examines consumer behavioural intention towards and willingness-to-pay for hydrogen-electric motorcycles in relation to perceived barriers, environmental concern, and socio-demographic variables	• Perception barriers (usage, value, risk, tradition, and price barrier) were statistically significant, with the price barrier being most significant. • Environmental concerns regulated the relationship between perception barriers and innovation resistance, with higher environmental concern resulting in a weaker positive relationship.
[12] 2018	No	• Develops and tests hypotheses regarding antecedents of anger, fear, joy, and pride about a local hydrogen fuelling station	• Perceived environmental impacts, perceived risks, and the perceived usefulness of the HFS for local citizens all significantly explained the rating of one or more emotional responses. • Perceived procedural and distributional unfairness explained anger and fear, while trust in industry had a significant positive effect on pride and a negative effect on fear.
[13] 2019	Yes	• Examines the effect of loss aversion and cognitive dissonance reduction on attitudes towards a hydrogen fuelling station, accounting for proximity to the site	• Support for the technology is stronger following its implementation, with perceived benefits weighing stronger and perceived risks weighing weaker for citizens in proximity to the site (<500m) • The above shift was detected for citizens living in closer proximity to the site, but does occur for the group living further away (>500m)
[14] 2019	Yes	• Investigates the acceptability of hydrogen energy technologies by citizens participating in hydrogen-related events (i.e. technology	• Participants in the technology introduction events tended to have lower levels of hydrogen knowledge than participants in professional seminars, but trust in HETs and acceptance of local HFSs was higher for the former group. • Socio-economic and environmental benefits had little impact on individual levels of acceptance of HETs.

		shows and professional seminars)	
[15] 2020	Yes	• Examines socio-psychological factors influencing general and local acceptance of emerging energy technologies including hydrogen fuelling stations	• Trust in one's municipality had no total effect on general acceptance, whereas it had a significant indirect effect and total effect on local acceptance. • Environmental self-identity had a positive indirect effect on acceptance at the general level, and a negative direct effect on acceptance at the local level, while problem perceptions had no significant effect.
[16] 2020	No	• Examines public perceptions and acceptance of domestic hydrogen	• Positive perceptions were associated with the impacts of hydrogen on the environment and energy performance. • Impacts on safety and the economy were viewed more neutrally, with concerns over disruptive impacts and distributional (in-)justice.
[17] 2020	No	• Examines how the physical and chemical characteristics of hydrogen influence social practices of heating and cooking, and consumer acceptance	• Hydrogen's near-invisible flame was regarded as more potentially disruptive to cooking practices than heating practices. • Flame visibility and behaviour were considered important indicators to cooking functionality and safety.
[18] 2021	Yes	• Examines consumer perspectives regarding potential social and technological barriers to the adoption of hydrogen fuel cell vehicles	• Consumer support for HFCVs (i.e. WTP) was influenced by the level of technology awareness, prior experience with the technology, media support, and the environmental sensitivity of the public. • Most respondents (>85%) believed HFCVs were as safe as conventional vehicles, therefore, no negative association between hydrogen safety and acceptance was observed.
[19] 2021	Yes	• Evaluates public trust in fuel, equipment, and self-handling technology for hydrogen-fuelling stations, in comparison to conventional gasoline stations	• Measures are needed to reduce anxiety related to the perceived psychological burden of station operation and maintenance, accident frequency, and difficulty using dispensers. • Familiarity with the technology, as derived via knowledge and experience, can strengthen acceptability, however, at present there is a substantial knowledge gap
[20] 2021	Yes	• Investigates consumers' purchase intention for a hydrogen fuel cell vehicle, and how environmental concern,	• Perceived social value had a significant positive association with consumer acceptance, while environmental concern was insignificant. • The positive association between green buying behaviour and purchase intention was positively associated with higher income.

			perceived social value, and green buying behaviour may affect purchase intention	
[21] 2022	Yes	•	Examines the factors influencing consumer attitudes towards and preferences for domestic hydrogen applications •	• Higher levels of support were observed for people who perceived themselves as early adopters of technology, with innovators expressing a preference for space and hot water heating applications. • Environmental and health benefits had a positive association for all hydrogen appliances, while disruptive impacts and inconvenience of the switchover had a negative association.
[22] 2022	Yes	•	Investigates the factors influencing consumer preferences for hydrogen fuel cell vehicles (HFCVs) and battery electric vehicles (BEVs)	• Most respondents lacked sufficient knowledge to discern the differences between each HFCVs and BEVs. • The longer driving range of FCEV, and fear of battery explosion significantly increase the likelihood of preferring FCEV. • Perceived BEV range sufficiency, tolerability in battery charging time, and fear of hydrogen explosion significantly increased the likelihood of preferring BEV. • Overall, safety concern had a stronger impact on adoption intention than purchase cost and perceived benefits.
[23] 2022	Yes	•	Examines consumers' awareness, perception, and intention to use hydrogen fuel cell vehicles	• Perceived benefits and higher income positively influenced intention to adopt, while perceived risk was negatively associated with consumer acceptance. • The main barriers to potential adoption included cost of the HFCV, hydrogen fuel price, and refuelling station proximity.
[24] 2022	No	•	Explores public perceptions related to the specific characteristics of a future hydrogen energy system, in relation to trade-offs, and the role of socio-demographic characteristics and attitudes	• Safety was the most important characteristic upon which respondents' willingness to support a hydrogen industry was contingent. • Climate change mitigation, affordability, reliability, accessibility, and job creation ranked behind safety.
[25] 2023	Yes	•	Examines public intention to adopt hydrogen fuel cell vehicles and their direct and indirect on influence on	• HFCVs must compete effectively with conventional automobiles in terms of perceived safety to enable consumer acceptance. • Consumers may be motivated to purchase HFCVs due to a desire to demonstrate environmental consciousness.

			Sustainable Development Goals (SDGs 7, 9, 11, 12, 13, 14 and 15)	• The cost acquisition and operating expenses substantially influenced consumer acceptance, while adoption of HFCVs had a positive impact of SDGs.
[26] 2023	No	•	Examines public perceptions for hydrogen mobile generators for use in public festivals, exploring the attitudes of audience members and local residents to the displacement of incumbent diesel generators	• Public awareness of hydrogen technology remains fairly low; however, information provision increases support levels. • Participants were concerned over the impact of hydrogen on future ticket prices for public festivals and query how these potential costs might be met, whereas concerns over safety are rarely voiced. • Support for green hydrogen was significantly higher than alternative production methods.
[27] 2023	No	•	Explores public perceptions of the UK Hydrogen Strategy and production pathways in the context of the domestic hydrogen transition	• Focus group participants appeared receptive to the UK Hydrogen Strategy but expressed reservations and uncertainty over the role of blue hydrogen. • Knowledge and awareness were positively associated with support for hydrogen. • Financial concerns and personal motivations outweighed environmental concerns.
[28] 2023	No	•	Evaluates technology preferences among existing gas users for switching to low-carbon hydrogen heating and cooking in comparison to electric-based alternatives	• Domestic hydrogen acceptance was positively associated with interest and engagement with renewable energy and fuel poverty pressures. • Safety assurances for hydrogen cooking were critical to fuel poor and young households. • Consumers appeared to favour the modernness, safety, and aesthetics of induction hobs, while emphasising the need for hydrogen boilers to be efficient, reliable, convenient, smart, and green.
[29] 2023	No	•	Examines social acceptance of green hydrogen at an early stage in its implementation, before wider rollout, in view of social trust and community participation	• Respondents demonstrated a lack of knowledge alongside a large degree of openness towards green hydrogen and its local use. • There are high expectations regarding environmental and climate protection via green hydrogen deployment, whereby support depends on social trust, distributional and procedural justice.
[30] 2023	Yes	•	Empirically tests the adoption of hydrogen fuel cell vehicles through the role of attitudes, perceptions, environmental	• Motivation and knowledge sharing have a significant effect on attitude toward HFCV adoption. • Perceptions of risk, cost, and infrastructure significantly impact HFCV adoption.

		concerns, and the effect of policy implications	
[31] 2023	Yes	• Analyses the needs motivating people to adoption hydrogen fuel cell vehicles	• Openness to experience and social influence had a strong positive influence on consumer motivation, followed by environmental concern and esteem needs. • Price consciousness had an insignificant effect on adoption motivation.
[32] 2023	No	• Examines public perceptions of hydrogen fuel cell vehicles in relation to personal and family situation, environmental awareness, energy attitude and local product confidence	• Gender, age, and income differences are not necessarily determinants of HFCV purchase, but educational level is a significant factor. • Personal awareness of environmental protection and energy attitudes positively predicted HFCV purchase. • Consumer confidence in Chinese local hydrogen products positively predicted HFCV purchase.
[33] 2023	Yes	• Evaluates consumer attitudes towards hydrogen homes by examining acceptance dynamics in relation public trust, financial perceptions, community benefits, disruptive impacts, and equity implications	• Trust deficits in the government and energy sector undermine the hydrogen transition. • Consumers desire market competition, choice, and fair prices for hydrogen appliances. • The spatial dynamics of the transition influence consumer perceptions of equity, with energy justice risks stressed by fuel poor households from industrial towns.

Table L-2. Methods and theoretical foundations for retrieved studies on hydrogen energy acceptance.

Study (SLR or SB)	Technology and country	Methods	Theoretical/conceptual foundation	Social acceptance dimensions
[1] **SLR**	• Hydrogen buses • Netherlands	• Online survey (N = 406) • Confirmatory factor analysis and multiple regression	• *Conceptual model linking trust and affective associations based on the risk perceptions literature*	• Attitudinal • Socio-political
[2] ***SB***	• Wind-hydrogen generation and storage • Scotland (Shetland Islands)	• Paper-based survey (N = 155) • Descriptive statistics and software visualisation	• Social Representation Theory	• Attitudinal • Community • Socio-political
[3] **SLR**	• Hydrogen fuel cell vehicles • South Korea	• Partial least squares structural equation modelling • Online survey and paper-and-pen interview (N = 295)	• *Socio-psychological approaches focused on needs, values, perceptions, and experience*	• Attitudinal • Behavioural • Market • Socio-political
[4] ***SB***	• Local hydrogen fuelling station • Netherlands	• Online survey (N = 1214) • Multiple regression analysis	• Norm Activation Model • Theory of Planned Behaviour	• Attitudinal • Behavioural • Community • Socio-political
[5] **SLR**	• Hydrogen energy technologies • Netherlands	• Online survey (N = 1133) • Covariance-based structural equation modelling	• Trust-based model	• Attitudinal • Socio-political
[6] **SLR**	• Local hydrogen fuelling station • Netherlands	• Online survey (N = 1214) • Covariance-based structural equation modelling	• Sustainable Energy Technology Acceptance Framework	• Attitudinal • Behavioural • Community • Socio-political
[7] ***SB***	• Local hydrogen fuelling station • Netherlands	• Online survey (N = 1214) • Covariance-based structural equation modelling	• Appraisal theory	• Attitudinal • Behavioural • Community • Market • Socio-political

[8] **SLR**	• Hydrogen economy and green hydrogen production • Taiwan	• Close-ended questionnaire: hand-outs and online access (N = 758) • Exploratory factor analysis • Multiple linear regression	• ***Unspecified***	• Attitudinal • Behavioural • Market • Socio-political
[9] ***SB***	• Hydrogen-electric motorcycles • Taiwan	• Questionnaire distributed to supermarket shoppers (N = 233) • Covariance based structural equation modelling	• *Conceptual model linking together product knowledge, perceived quality, perceived risk, perceived value, and purchase intentions*	• Attitudinal • Market
[10] **SLR**	• Local hydrogen fuelling station • Japan	• Online survey (N = 2069) • Exploratory factor analysis • Stepwise binomial and logit regression analyses	• Adapted Sustainable Energy Technology Acceptance Framework	• Attitudinal • Behavioural • Market • Socio-political
[11] **SLR**	• Hydrogen-electric motorcycles Taiwan	• Paper questionnaire (N = 232) • Contingent valuation method • One-way analysis of variance and multiple regression analysis	• Theory of innovation resistance	• Attitudinal • Behavioural • Market • Socio-political
[12] **SLR**	• Local hydrogen fuelling station • Netherlands	• Paper-and-pencil survey with local residents (N = 271) • Multiple regression analysis	• Appraisal theory • Sustainable Energy Technology Acceptance Framework	• Attitudinal • Behavioural • Community • Socio-political
[13] ***SB***	• Local hydrogen fuelling station • Netherlands	• Pen-paper survey (N = 279: N = 172 pre-HFS installation; N = 108 post-HFS installation) • Quasi-experimental, between-subject design • Descriptive statistics • Hierarchal regression analysis and simple slopes analysis	• *Loss aversion and cognitive dissonance theory*	• Attitudinal • Community
[14] **SLR**	• Hydrogen energy technologies • Japan	• Online survey (N = 540) • Covariance based structural equation modelling	• *Conceptual model linking trust in technology, and knowledge and awareness*	• Attitudinal • Behavioural • Community

				• Socio-political
[15] **SLR**	• Hydrogen fuelling stations • Germany	• Covariance-based structural equation modelling • Online survey (N = 409)	• Adapted Sustainable Energy Technology Acceptance Framework	• Attitudinal • Community • Market • Socio-political
[16] **SLR**	• Domestic hydrogen technologies • England	• Online survey (N = 700) • Paper-based survey (N = 102) • Mixed-methods approach based on grounded theory	• Triangle of Social Acceptance • Social Representations Theory • Theory of Planned Behaviour	• Attitudinal • Behavioural • Community • Market • socio-political
[17] ***SB***	• Domestic hydrogen technologies • United Kingdom	• Paper-based survey and follow-up interviews (N = 100) • Talking-methodology Thematic analysis and descriptive statistics	• Social Practice Theory	• Attitudinal • Behavioural
[18] **SLR**	• Hydrogen fuel cell vehicles • Denmark	• Online survey (N = 158) • Covariance-based structural equation modelling	• Technology Acceptance Model (TAM3)	• Attitudinal • Market • Socio-political
[19] **SB**	• Hydrogen fuelling stations • Japan	• Online survey (N = 300) • Descriptive statistics • One-way analysis of variance	• Conceptual model linking trust in technology, and knowledge and awareness	• Attitudinal • Behavioural • Socio-political
[20] ***SB***	• Hydrogen fuel cell vehicles • China	• Online survey (N = 300) • Covariance-based structural equation modelling	• Norm Activation Model • Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[21] **SLR**	• Domestic hydrogen technologies and hydrogen energy technologies for export • Australia	• Online survey (n=906) • Multivariate regression analysis	• Extended Sustainable Energy Technology Acceptance Framework	• Attitudinal • Behavioural • Community • Market • Socio-political
[22] **SLR**	• Hydrogen fuel cell vehicles • Australia	• Online survey (N = 1735) • Descriptive statistics	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market

		• Partial least squares structural equation modelling (N = 1722) • Multinomial logistic regression		• Socio-political
[23] ***SB***	• Hydrogen fuel cell vehicles • India	• Online survey (N = 483) • Partial least squares structural equation modelling	• Theory of Planned Behaviour • Unified Theory of Acceptance and Use of Technology	• Attitudinal • Behavioural • Community • Market • Socio-political
[24] **SLR**	• Hydrogen energy industry • Australia	• Online survey (N = 1824) • Descriptive statistics • Fractional multinomial logistic regression	• ***Unspecified***	• Attitudinal • Market • Socio-political
[25] **SLR**	• Hydrogen fuel cell vehicles • India	• Online survey (N = 358) • Partial least squares structural equation modelling	• Theory of Planned Behaviour	• Attitudinal • Behavioural • Community • Market • Socio-political
[26] **SLR**	• Hydrogen-powered mobile generators • Scotland	• In-situ surveys (N = 340) • Online focus group sessions (N = 25) • Descriptive statistics • Thematic analysis and content analysis	• Triangle of social acceptance • Five dimensions of domestic hydrogen acceptance	• Attitudinal • Community • Market • Socio-political
[27] **SLR**	• Domestic hydrogen technologies • United Kingdom	• Online focus groups (N = 45) • Mixed-methods multigroup analysis • Descriptive statistics and correlation analysis • Thematic and content analysis	• Five dimensions of domestic hydrogen acceptance	• Attitudinal • Behavioural • Market • Socio-political
[28] **SB**	• Domestic hydrogen technologies • United Kingdom	• Online focus groups (N = 45) • Mixed-methods multigroup analysis	• ***Unspecified***	• Attitudinal • Behavioural

		• Descriptive statistics and correlation analysis • Thematic and content analysis		
[29] **SLR**	• Green hydrogen production, infrastructure, and technologies • Germany	• Mixed-methods analysis: representative only survey (N = 2054); semi-structured interviews (N = 24); and two participatory workshops (N = 51) • Descriptive statistics and linear regression analysis • Qualitative analysis	• Triangle of social acceptance • *Responsible Innovation*	• Attitudinal • Behavioural • Community • Socio-political
[30] **SLR**	• Hydrogen fuel cell vehicles • India	• Structured questionnaire using a multi-stage stratified sampling (N = 441) • Partial least squares structural equation modelling	• Theory of Reasoned Action • Theory of Planned Behaviour • *Perception-attitude-adoption (intention) paradigm*	• Attitudinal • Behavioural • Community • Market • Socio-political
[31] ***SB***	• Hydrogen fuel cell vehicles • India	• Structured questionnaire using a multi-stage stratified sampling (N = 380) • Multiple regression analysis • Partial least squares structural equation modelling	• *Maslow's Hierarchy of Needs model*	• Attitudinal • Behavioural • Market • Socio-political
[32] **SLR**	• Hydrogen fuel cell vehicles • China	• Online survey (N = 600) • Ordinal least squares and logistic regression	• *Behavioural economic theory*	• Attitudinal • Market • Socio-political
[33] **SB**	• Domestic hydrogen technologies • United Kingdom	• Online focus groups (N = 45) • Mixed-methods multigroup analysis • Descriptive statistics and correlation analysis • Thematic and content analysis	• Five dimensions of domestic hydrogen acceptance	• Attitudinal • Behavioural • Community • Market • Socio-political

Table L-3 and Table L-4 report information on studies retrieved via the SLR on domestic energy acceptance. Firstly, Table L-3 reports the year of the study, whether a theoretical, conceptual, or empirical model was included, the aims and scope, and key findings. Table L-4 reports whether the study was retrieved via SLR or through subsequent snowballing (SB), the technology analysed and corresponding national context(s), methods and theoretical or conceptual foundations, and the number of social acceptance dimensions engaged within the empirical analysis.

Table L-3. Aims and findings for retrieved studies on domestic energy acceptance (N = 42).

Study and year	Theoretical or conceptual model included	Aims and scope	Key findings on consumer acceptance
[34] 1993	No	• Explores the public acceptance of solar domestic water heating, focusing on householder consideration of, and decision-making in new homes	• Householders typically establish technical feasibility before serious consideration of the solar option, and financial viability before adoption. • Friends, neighbours, and social networks are very important in communicating relevant information. • Government agencies and electricity authorities play a limited role.
[35] 2011	No	• Investigates willingness to pay (WTP) for microgeneration technologies and the relative influence of subjective consumer perceptions	• Perceived benefits of energy independence increases WTP for wood pellet boilers and solar panels, while perceived social risk had a negative effect on WTP for wind turbines. • Uncertainty related to technology performance had a negative influence on WTP for solar heaters and wood pellet boilers, while higher WTP for solar panels is associated with environmental benefits.
[36] 2012	No	• Evaluates the purchasing probability of rooftop solar PV among grid-connected homeowners	• Perceived cost, maintenance requirement, and environmental concern were the most important determinants of consumer acceptance. • Consumer perceptions are influenced by the aesthetics of solar panels, availability of financial programs and regulation from Homeowner Associations.
[37] 2013	No	• Examines the multi-dimensionality of homeowners' motivation to decide between	• Energy standard and dwelling size had a significant influence on adoption motivation, whereas household income had only a weak influence on consumer attitudes.

		competing residential heating systems	• People living in larger homes were more sensitive to cost factors, while owners of newly built homes were less sensitive to cost, especially when energy efficiency ratings were high.
[38] 2014	Yes	• Measures consumer propensity to adopt smart meters in residential buildings and interactions between critical factors	• The critical determinants of consumer acceptance were perceived usefulness and perceived ease of use, and perceived risks related to energy costs, privacy, and safety. • The influence of perceived risk on user expected satisfaction was partially mediated by perceived usefulness and perceived ease of use.
[39] 2014	Yes	• Examines how residential electricity consumers perceive the smart grid and what factors influence their acceptance	• Understanding of the smart grid improved perceptions regarding ease of use and usefulness. • Perceptions of understanding and compatibility with existing technology influenced perceived ease of use and energy, environmental, and financial benefits. • Mitigating anxiety about perceived risks is required, especially in relation to concerns about the electromagnetic radiation from smart meters.
[40] 2014	Yes	• Examines the impact of environmental value, ecological lifestyle, and customer innovativeness on intention to install rooftop solar PV	• Environmental value had a positive impact on ecological lifestyle and intention to install. • Customers who actively seek and process information were more likely to install solar PV • There is more scope for altering an individual's lifestyle than altering their personal values or personality to support solar PV adoption.
[41] 2015	No	• Explores individual-level perceptions and information gaps associated with the adoption of rooftop solar PV	• Perceived behavioural control had a significant effect on adoption intention or calling installers for quotes. • Respondents look to others for information about the technology due to a knowledge deficit in view of technical complexity. • Environmental concern and perceived affordability become influential factors as respondents move through the decision-making process.
[42] 2016	Yes	• Examines the predictors of intention to adopt sustainable household energy technologies	• Product attributes including performance, compatibility, and hedonic expectancy significantly predicted adoption intention, as well as consumer characteristics (specifically sustainable innovativeness). • Effort expectancy, environmentalism, and social pressure were non-significant.

[43] 2017	Yes	• Evaluates the factors governing rooftop solar PV acceptance and its usage among users	• Perceived ease of use had a stronger impact on behavioural intention than perceived usefulness. • A weak positive relationship was observed between these two variables.
[44] 2017	No	• Investigates householders' preferences towards and WTP for key features of wood pellet fired heating systems	• Knowledge was a positive and significant predictor of WTP for both early adopters and intermediates, but not for laggards, while acceptance is positively associated with strong environmental values. • CO_2 emissions influenced consumer acceptance for early adopters, while late adopters were more concerned with technical and economic factors.
[45] 2017	Yes	• Analyses the patterns of intention-behaviour gap in solar energy adoption and its impacts of social acceptance	• Respondents expressed general positivity towards solar PV, which was often counteracted by personal apathy towards adoption. • Social acceptance was suppressed by a mix of undesirable contextual conditions such as lack of information, technical knowledge, subsidies, political commitment, affordability etc.
[46] 2017	Yes	• Investigates consumer acceptance of a HEMS, including the impact of awareness on intention to use	• Economic benefit had the most significant influence on perceived usefulness, followed by social contribution, and environmental responsibility. • Perceived usefulness had a larger effect on intention to use than perceived ease of use, while innovativeness has a positive effect on perceived ease of use and perceived usefulness.
[47] 2017	Yes	• Investigates a set of socio-psychological predictors affecting smart meter support and intention to adopt	• Perceived usefulness positively predicted support for smart meter installation and adoption, while risk to privacy was negatively associated with acceptance and perceived cost had no impact. • Perceived usefulness was the strongest mediator variable, while problem perception had a direct influence on perceived usefulness.
[48] 2017	Yes	• Investigates the psychological and social determinants of interest in rooftop solar PV adoption by integrating three theoretical approaches (DoI, TBP, VBN)	• Individuals who trust installers and believe solar will be personally beneficial were more likely to consider contacting an installer, as are individuals drawn to novel products. • Consumers may seek trustworthy information about the costs and performance of rooftop solar PV from personal acquaintances in their social networks. • The integrated framework yields more predictive power than operationalising the theories in isolation.

[49] 2017	Yes	• Examines non-solar panel users' intention to purchase the technology	• Product benefits, social influence, product knowledge and experience, perceived costs and maintenance had a direct and positive impact on purchase intention. • Perceptions of government policy, solar panel aesthetics, and demographic factors (income and education level) were insignificant predictors.
[50] 2018	Yes	• Quantifies how a set of individual and community level factors influence adoption intention for rooftop solar PV	• Visual exposure to solar technology had a strong effect on intention, lending support to social learning and social network theories of diffusion of innovation. • Perceived knowledge of energy systems and being publicly engaged in energy issues significantly increases adoption intention. • However, factual knowledge of energy systems was not a significant predictor of solar adoption intention.
[51] 2018	No	• Evaluates the extent to which factors from different theoretical models of technology acceptance explain household adoption of solar water heaters	• Perceived relative advantage, compatibility, and observability increased the likelihood of adoption, whereas complexity reduced adoption potential. • Social norms were significant when people are able to demonstrate their social inclusiveness to the local community, while adopters had a relatively high novelty-seeking motivation.
[52] 2018	Yes	• Assesses the public's disposition toward a smarter electricity grid and attitudes towards green energy, smart meters and becoming prosumers	• Cost savings proved the strongest motivator of smart meter adoption, while environmental benefits were also a significant driver. • Perceived inconvenience had a weak negative association, while past experience using energy saving appliances positively predicted consumer acceptance.
[53] 2018	Yes	• Investigates the factors which affect people's choice of energy-efficient homes and their satisfaction with their residences	• Consumer acceptance was shaped by health and environmental consciousness, consideration of local of communities, active use of smart technologies, and factors related to choice of residence (e.g. co-services and related benefits).
[54] 2019	Yes	• Examines the factors which influence the purchase intent of domestic solar PV adopters	• Social beliefs were the most significant determinant of purchase intent, followed by effort expectancy and price-value beliefs. • Self-efficacy (i.e. confidence in the installation process and financial capacity) had the least significance in the model.
[55] 2019	Yes	• Empirically tests whether different motivational drivers	• The goal trigger grounded on normative motivations was most influential, while the socio-economic level of the household moderated this effect.

		influence consumer intention to purchase green energy	• Individuals with a high socio-economic level significantly increased their purchase intention if motivated by a normative goal. • Individuals with a medium socio-economic level were mostly motivated by goal triggers grounded on economic benefits
[56] 2019	No	• Evaluates the factors influencing the purchase of rooftop solar PV	• Perception of relative advantage was positively associated with consumer acceptance, with the perceived advantages including long-term non-economic benefits, such as environmental protection and provision of unlimited power. • Installation cost proved the most significant adoption barrier.
[57] 2019	No	• Evaluates willingness to adopt (WTA) and WTP for domestic energy technologies in a hybrid system	• Residence-related factors (e.g. type of dwelling, year of construction and size etc.) had a significant impact on consumers' intentions. • Males expressed a higher WTP and accept a longer payback period, while higher educational level and monthly income were positively associated with acceptance, whereas installation cost is perceived as a barrier to acceptance.
[58] 2019	Yes	• Investigates the factors that influence residents' acceptance and usage of smart homes	• Perceived usefulness had the most significant (positive) affect intention to use, followed by attitudinal variables (e.g. perceived enjoyment), and trust factors. • Awareness of smart homes was positively associated with attitudinal acceptance, whereas perceived risks had a negative impact on users' trust in smart homes and associated acceptance.
[59] 2020	Yes	• Examines nonusers' behavioural intention to adopt rooftop solar PV	• Social influence had the greatest impact of intention to install solar PV, with a positive indirect effect on facilitating conditions. • Price value and knowledge affected social influence positively and significantly, with the former having a more significant effect.
[60] 2020	Yes	• Investigates the factors influencing households' purchase intention of rooftop solar PV	• Perceived usefulness and perceived ease of use positively and significantly shaped consumer attitude toward technology adoption. • Consumer attitude had a positive and significant impact on purchase intention. • Perceptions of governmental policy and propaganda moderated the relationship between consumer attitude and purchase intention.
[61] 2020	Yes	• Examines the relationship among personal traits, psychological benefits,	• Government incentives had the strongest influence on intention to install rooftop solar PV, corresponding to a direct and positive effect.

			attitudes, government incentives, and intention to install rooftop solar PV	• Ecological lifestyle, consumer innovativeness, and warm glow positively predicted intention to install through attitude towards rooftop solar PV.
[62] 2020	Yes	•	Investigates the factors shaping end-user acceptance for a household energy management system (HEMS) by exploring peoples' intentions to use the technology for residential demand-side management	• Relevance of the HEMS to domestic energy management goals, stronger environmental worldview, and goal internalisation (regarding national energy goals) had a positive, indirect relationship with intention to use via perceived usefulness. • Subjective norms and perceived voluntariness were neither related to perceived usefulness nor intentions to use a HEMS.
[63] 2020	Yes	•	Examines the factors influencing the decisions of (low-income) residential electricity consumers regarding demand-side management and distributed energy resources	• Potential reduction of electricity-related expenditure proved the strongest driver of consumer acceptance, while concerns were expressed over up-front costs and maintenance costs, and lack of information. • Opportunities to choose between different energy suppliers/sources motivated consumer acceptance.
[64] 2020	Yes	•	Examines attitudes towards and acceptance of energy storage at the household and community level in relation to causal variables.	• Age (being younger) significantly and positively predicted acceptance, whereas financial cost was perceived as a barrier to adoption. • Negative attitudes correlated negatively with willingness to install a battery home system, while affective dimensions were influential factors of acceptance.
[65] 2021	Yes	•	Analyses the factors influencing consumers' willingness to utilise solar energy for household purposes	• Intention factors (perception about self-effectiveness, environmental concern, awareness of solar energy, and belief of solar energy benefits) had a positive influence on consumer willingness, while cost of solar has a negative effect. • Perceptions of neighbour's participation in solar adoption had an insignificant effect.
[66] 2021	Yes	•	Develops a smart meter acceptance model to evaluate the moderation role of experience and personal innovativeness factors among residential consumers	• Experience moderated the relationship between effort expectancy, habit, and privacy concerns on behavioural intention. • Personal innovativeness moderated the relationship between privacy concerns on behavioural intention.

[67] 2021	Yes	• Investigates the predictors and mediators of intention to adopt rooftop solar PV	• Environmentalism had a significant impact on adoption intention, followed by knowledge. • Perceived usefulness mediated the relationship between environmentalism and knowledge, and the intention to use solar PV. • However, no mediation effect was observed for perceived ease of use.
[68] 2021	Yes	• Explores the antecedents of consumer willingness to adopt rooftop solar PV	• Social norms, perception of self-efficacy, and belief about solar PV benefits positively influenced adoption potential. • Perceived risks and financial perceptions of solar PV had a negative effect. • Openness to technology had an insignificant effect on willingness to adopt.
[69] 2021	Yes	• Investigates the psychological attributes influencing adoption intention for a household energy-saving option (HESO)	• Perceived value was the dominant influencing factor of adoption intention, as determined by three variables: perceived usefulness, perceived enjoyment, and time consumption. • Perceived usefulness had the strongest positive correlation with perceived value. • The relationship between perceived value and the adoption intention is negatively moderated by households' perception of risks associated with HESO trading.
[70] 2022	Yes	• Examines the factors influencing smart energy technology acceptance and adoption	• Perceived ease of use, attitudinal constructs, trust, knowledge, awareness, social influence, and policy had a significant influence on behavioural intention. • Perceived ease of use and attitudes towards using the technology had a positive effect, while perceived usefulness has no influence on behavioural intention.
[71] 2022	Yes	• Examines intentions and attitudes towards adopting rooftop solar PV	• Attitude positively predicted intention to use rooftop solar PV. • Environmental awareness had a positive effect on consumer's attitudes towards rooftop solar PV, whereas perceived costs had a negative effect. • Perceived relative advantage increased adoption potential.
[72] 2022	Yes	• Investigates the factors influencing households' purchase intentions of rooftop solar PV	• Product knowledge, ecological lifestyle, perceived benefits, innovativeness, and optimism positively and significantly impacted consumers' attitudes toward rooftop solar PV. • Consumer attitude had a positive and significant impact on purchase intention.

			• The moderating role of perceived consumer effectiveness in the relationship between consumer attitudes and purchase intentions was significantly correlated.
[73] 2022	Yes	• Examines the determinants of intention to purchase rooftop solar PV	• Environmental concern, green perceived usefulness, perceive ease of use were positively associated with attitude and intention to purchase rooftop PV panel system. • Attitude, perceived behavioural control and awareness were positively related to intention to purchase rooftop PV panel system.
[74]	Yes	• Investigates the effect of female consumers' occupations, including full-time housewives and employed females, on their acceptance of smart washing machines	• Full-time housewives placed greater emphasis on utilitarian benefits, therefore enhanced convenience and efficiency of laundry play crucial roles in their acceptance process. • Employed females perceive both utilitarian and hedonic benefits to be significant, indicating that technical advances, as well as psychological and social pleasure are important predictors of technology acceptance
[75] 2023	Yes	• Examines the factors influencing the use and purchase of energy-saving electrical appliances	• Perceived usefulness and perceived ease of use had significant relationships with attitude and behavioural intention. • Moderating effects of perceived behavioural control to the relationships between perceived ease of use and perceived usefulness was insignificant. • Moderating effects of affordability on the relationship between behavioural intention and attitude were insignificant.

Table L-4. Methods and theoretical foundations for retrieved studies on domestic energy acceptance.

Study (SLR or SB)	Technology and Country	Methods	Theoretical/conceptual foundation	Social acceptance dimensions
[34] **SLR**	• Solar water heaters • Australia	• Telephone interviews (N = 452) • Descriptive statistics • Factor analysis	• Diffusion of Innovation Theory	• Attitudinal • Behavioural • Market • Community • Socio-political
[35] ***SB***	• Domestic microgeneration technologies[b] • Republic of Ireland	• Computer assisted telephone interviews (N = 1012) • Contingent valuation approach • Bivariate probit model	• Diffusion of Innovation Theory	• Attitudinal • Behavioural • Market • Socio-political
[36] **SLR**	• Rooftop solar PV • United States	• Online survey (N = 475) • Quantitative modelling method (fuzzy logic)	• Triangle of Social Acceptance	• Attitudinal • Market
[37] ***SB***	• Domestic microgeneration technologies[c] • Germany	• Self-administered questionnaire (N = 2440) • Principal component analysis and cluster analysis	• Extended Diffusion of Innovation Theory • Extended Technology Acceptance Model • Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[38] **SLR**	• Smart meters • Indonesia	• Paper-based survey (N = 301) • Covariance-based structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market
[39] **SLR**	• Smart grids • South Korea	• Questionnaire collected through personal interviews (N = 255) • Covariance-based structural equation modelling	• Extended Technology Acceptance Model (Design of Risk integrated TAM)	• Attitudinal • Behavioural • Market • Socio-political
[40] ***SB***	• Rooftop solar PV • Taiwan	• Paper-based survey (N = 203) • Covariance-based structural equation modelling	• Diffusion of Innovation Theory • Extended Theory of Planned Behaviour	• Attitudinal • Behavioural

[41] **SLR**	• Rooftop solar PV • United States	• Paper-based survey (N = 522) • Logistic and order probit regression analysis	• Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[42] ***SB***	• Sustainable household and smart technologies • United States	• Online survey (N = 592) • Covariance-based structural equation modelling	• Unified Theory of Acceptance and Use of Technology	• Attitudinal • Behavioural • Market • Socio-political
[43] **SLR**	• Rooftop solar PV • Malaysia	• Personal administrated survey (N = 663) • Confirmatory factor analysis • Multiple regression analysis	• Technology Acceptance Model	• Attitudinal • Behavioural • Market
[44] ***SB***	• Wood pellet fired heating systems • Italy	• Web-based computer aided survey (N = 1451) • Choice experiment • Latent class-random parameter model	• Diffusion of Innovation Theory	• Attitudinal • Behavioural • Market • Socio-political
[45] **SLR**	• Rooftop solar PV • Finland	• Semi-structured interviews (N = 42)[d] • Purposive and snowball sampling strategies • Qualitative comparative analysis	• Diffusion of Innovation Theory • Theory of Planned Behaviour	• Attitudinal • Community • Market • Socio-political
[46] ***SB***	• Home Energy Management System • South Korea	• Online survey (N = 287) • Partial least squares structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market • Socio-political
[47] ***SB***	• Smart meters • United States	• Online survey (N = 711) • Covariance-based structural equation modelling	• Extended Technology Acceptance Model • Extended Sustainable Technology Acceptance Model	• Attitudinal • Behavioural • Market • Socio-political

[48] ***SB***	• Rooftop solar PV • United States	• Online survey (N = 904) • Covariance-based structural equation modelling • Nested sequence of ordinal least squares multiple regressions	• Diffusion of Innovation • Theory of Planned Behaviour • Values-Beliefs-Norms Theory	• Attitudinal • Behavioural • Market • Socio-political
[49] ***SB***	• Rooftop solar PV • Malaysia	• Self-administered questionnaire (N = 211) • Descriptive statistics • Reliability, correlational and regression analysis	• Diffusion of Innovation Theory • Theory of Reasoned Action	• Attitudinal • Behavioural • Community • Market • Socio-political
[50] ***SB***	• Rooftop solar PV • Canada	• Online survey (N = 2065) • Covariance-based structural equation modelling	• Knowledge Deficit Model • Values-Beliefs-Norms Theory	• Attitudinal • Behavioural • Socio-political
[51] ***SB***	• Solar water heaters • Lebanon	• Household survey, conducted through face-to-face interviews (N = 200) • Binary logistic regression (backward stepwise likelihood ratio)	• Extended Diffusion of Innovation Theory • Extended Values-Beliefs-Norms Theory	• Attitudinal • Behavioural • Community • Market • Socio-political
[52] **SLR**	• Smart grids and smart metering • Saudi Arabia	• Face-to-face interviews with household decision makers (N = 228) • Logistic regression model	• Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[53] **SLR**	• Energy-efficient home technologies • Japan	• Online survey (N = 619) • Multivariate probit model	• Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Community • Market
[54] **SLR**	• Rooftop solar PV • India	• Structured Optical Mark Reader questionnaire (N = 400 • Exploratory factor analysis • Multiple regression analysis	• Unified Theory of Acceptance and Use of Technology	• Attitudinal • Behavioural • Market • Socio-political

[55] ***SB***	• Rooftop solar PV • Mexico	• Face-to-face survey (N = 72): field experiment investigating different goal triggers for purchase intention • Descriptive statistics • Group comparison (Mann–Whitney test) • Analysis of covariance	• Extended Theory of Planned Behaviour • Goal framing theory	• Attitudinal • Behavioural • Market • Socio-political
[56] **SLR**	• Rooftop solar PV • Saudi Arabia	• Online survey (N = 1498) • Multiple regression analysis	• Diffusion of Innovation Theory	• Attitudinal • Behavioural • Community • Market • Socio-political
[57] **SLR**	• Residential hybrid system for heating/cooling and hot water[e] • Greece, Portugal, and Spain	• Online survey (N = 400) • Ordinal logistic regression	• Diffusion of Innovation Theory • Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market • Socio-political
[58] **SLR**	• Smart homes • Jordan	• Online survey (N = 285) • Partial least squares structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural
[59] **SLR**	• Rooftop solar PV • Malaysia	• Paper-based questionnaire (N = 392) • Partial least squares structural equation modelling	• Unified Theory of Acceptance and Use of Technology and UTAUT2	• Attitudinal • Market • Socio-political
[60] ***SB***	• Rooftop solar PV • Pakistan	• Paper-based questionnaire (N = 435; purposive sampling) • Partial least squares structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market • Socio-political
[61] ***SB***	• Rooftop solar PV • Taiwan	• Online survey (N = 300) • Covariance-based structural equation modelling	• Extended Theory of Planned Behaviour • Self-determination theory	• Attitudinal • Behavioural • Market

				• Socio-political
[62] **SLR**	• Home energy management system for residential demand-side management • United Kingdom	• Online Information and Choice Questionnaire (N = 107) • Ordinal least squares regression analysis	• Extended Technology Acceptance Model and TAM2	• Attitudinal • Behavioural • Community • Socio-political
[63] **SLR**	• Demand-side management and distributed energy resources • Japan	• Paper-based questionnaire (N = 207) • Multivariate regression analysis	• Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[64] **SLR**	• Distributed energy storage technologies (i.e. batteries) • United Kingdom	• Online survey (N = 949) • Hierarchical regression analysis	• Extended Sustainable Energy Technology Acceptance model	• Attitudinal • Behavioural • Community • Market • Socio-political
[65] ***SB***	• Rooftop solar PV • China	• (N = 355) • Covariance-based structural equation modelling	• Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Community • Market • Socio-political
[66] **SLR**	• Smart meters • Malaysia	• Online survey (N = 318) • Partial least squares structural equation modelling	• Unified Theory of Acceptance and Use of Technology (UTAUT2)	• Attitudinal • Behavioural • Market
[67] **SLR**	• Rooftop solar PV • Malaysia	• Self-administered questionnaires (N = 200)	• Extended Technology Acceptance Model	• Attitudinal • Behavioural
[68] ***SB***	• Rooftop solar PV • Pakistan	• Self-administered questionnaire (N = 683) • Covariance-based structural equation modelling	• Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[69] **SLR**	• Household Energy Saving Option	• Paper-based questionnaire (N = 446)	• Value-Based Adoption Model*	• Attitudinal • Behavioural

	• Singapore	• Snowball sampling technique (online and on-site recruitment) • Partial least squares structural equation modelling		• Community • Market
[70] **SLR**	• Smart energy technologies for domestic use • Denmark	• Online survey (N = 3205) • Multiple linear regression analysis	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market • Socio-political
[71] **SLR**	• Rooftop solar PV • Saudi Arabia	• Online survey (N = 492) • Partial least squares structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Market
[72] ***SB***	• Rooftop solar PV • Pakistan	• Self-administered questionnaire (N = 311) • Partial least squares structural equation modelling •	• Extended Theory of Planned Behaviour; integrating the Technology Readiness Index	• Attitudinal • Behavioural • Community • Socio-political
[73] ***SB***	• Rooftop solar PV • South Africa	• Self-administered questionnaire (N = 402) • Partial least squares structural equation modelling	• Technology Acceptance Model • Extended Theory of Planned Behaviour	• Attitudinal • Behavioural • Market • Socio-political
[74] ***SB***	• Smart washing machines • South Korea	• Self-administered questionnaire (N = 380) • Covariance-based structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Socio-political
[75] **SLR**	• Energy-saving appliances • Sri Lanka	• Online survey (N = 384) • Partial least squares structural equation modelling	• Extended Technology Acceptance Model	• Attitudinal • Behavioural • Community • Market • Socio-political

Table L-5 reports the variables included in the Sustainable Energy Technology Acceptance (SETA) model, defined according to the broader context of hydrogen energy technologies (HETs). ***Bold italics*** represent constructs that are retained within the Domestic Hydrogen Acceptance Model (DHAM). Fig. L-1 provides information on citations counts on SETA by energy journals for the period 2013–2022, while Fig. L-2 provides a network visualisation of connected keywords in the Scopus dataset.

Table L-5. SETA Model applied to hydrogen energy acceptance.

Acceptance predictor	Definition in the context of hydrogen energy acceptance
Experience	• Direct or indirect exposure and engagement with hydrogen energy technologies, and associated awareness and familiarity levels
Knowledge	• Perceived subjective knowledge of hydrogen fuel and hydrogen energy technologies, and objective knowledge of hydrogen properties, characteristics, and applications
Social Trust	• Trust in the key actors and stakeholders responsible for the implementation of hydrogen infrastructure and technologies
Procedural fairness	• Perceived fairness regarding the decision-making processes of developing and implementing hydrogen infrastructure and technologies
Distributive fairness	• Perceived fairness regarding the distribution of benefits, costs, and risks of developing and implementing hydrogen infrastructure and technologies
Positive affect	• Feelings of satisfaction, calmness, confidence, optimism, and other positive emotions towards hydrogen energy technologies
Negative affect	• Feelings of discontent, worry, fear, pessimism, and other negative emotions towards hydrogen energy technologies
Perceived benefits	• Perceptions of potential macro-economic, social, environmental, community, and individual benefits associated with hydrogen energy technologies
Perceived costs	• Perceptions of potential macro-economic, social, environmental, community, and individual costs associated with hydrogen energy technologies
Perceived risks	• Perceptions of potential risks and disruptive impacts linked to the development and implementation of hydrogen infrastructure and technologies, typically pertaining to safety concerns
Outcome efficacy	• The extent to which an individual can contribute towards enacting effective solutions to the perceived problem(s)
Problem perception	• Awareness of problems related to the current energy system such as adverse environmental effects (i.e. climate change, pollution, and loss of biodiversity), energy insecurity, and fuel poverty
Personal norm	• A moral or normative obligation to support/oppose or adopt/reject hydrogen infrastructure and technologies, stemming from the perceived social pressure to perform such behaviours
Social norm	• The degree to which individual beliefs about hydrogen are shaped by the influence of important members of their social networks or local community

Perceived behavioural control	• The perceived ease of difficulty of adopting a specific hydrogen energy technology
Attitude	• The degree to which an individual has a favourable or unfavourable evaluation of supporting or adopting hydrogen energy technologies, according to the likelihood that a given behaviour has specific outcomes, and the evaluation of these outcomes
Intention to accept[a]	• The behavioural intention to support and adopt hydrogen energy technologies, as predicted by attitudinal acceptance (i.e. attitude towards support and adoption) and other factors specified within the framework

Source: Authors' compilation based on [7,76–78].

[a] Formulated as 'willingness to adoption domestic hydrogen".

Results from keyword search on SETA

A keyword search was performed in Scopus (all fields) for "sustainable energy technology acceptance," which returned 541 journal articles in English for the period 2012–2022. In total, eight journals hold more than ten articles matching the keyword search, which combined account for 41% of all results until 2022 (N = 224). As shown in Fig. L-1, the citation count grew exponentially to 2020 before stabilising in subsequent years. However, as of September 2023 there are already 74 citations matching the search (N = 615), confirming a resurgence of research growth on this topic, which was possibly stifled during COVID-19. The two most featured journals representing publications on SETA between 2013 and 2022 are Energy Research & Social Science (N = 59) and Energy Policy (N = 54), followed by Sustainability Switzerland (N = 36) and Energies (N = 22), while the remaining four journals account for just under a quarter of citations (N = 53).

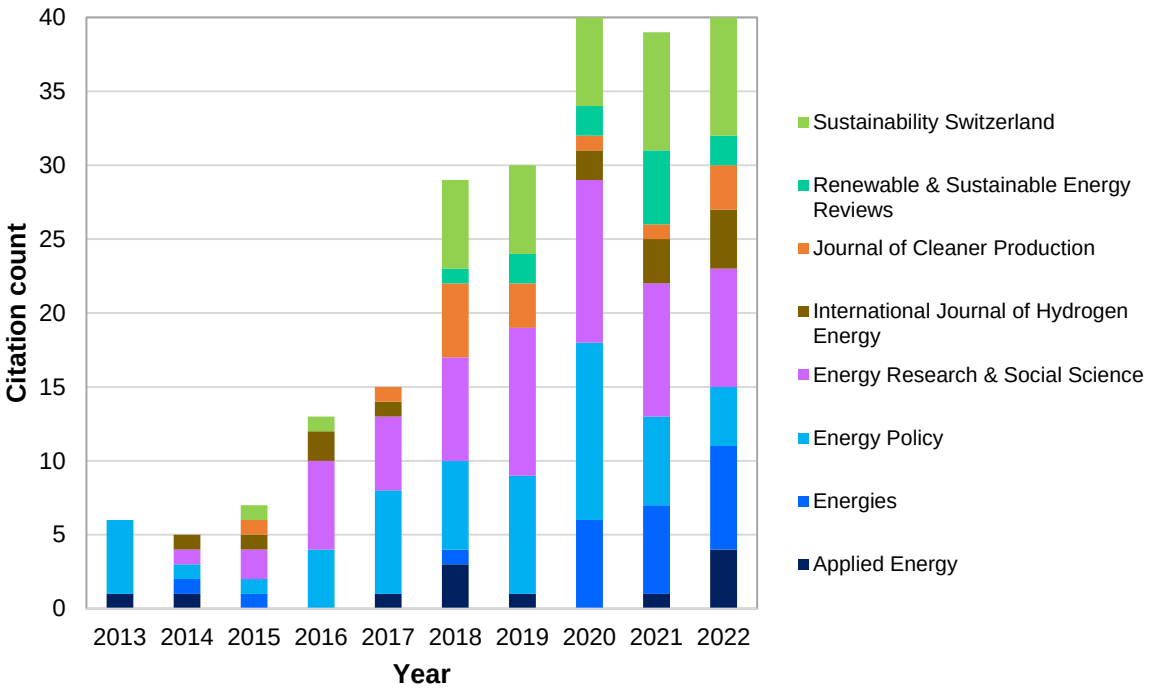

Fig. L-1. Citation count on sustainable energy technology acceptance by top eight journals, 2013–2022.

Bibliometric analysis of sustainable energy technology acceptance

The VOSviewer bibliometric software tool [79] helped visualise additional insights from across the 620 journal articles retrieved by Scopus (2013–2023). The main themes were extracted by exploring the relationships between connected keyword items. Given the large number of keywords included in the data (N = 4190), the minimum number of keyword occurrences was set to 20 (50 met the threshold). This adjustment supported higher resolution findings with a more concentrated number of clusters (N = 5).[1] As illustrated in Fig. L-2, three main clusters emerged, consisting of 18, 15, and 12 items. The largest cluster (red) included keywords such as social acceptance, social aspects, public attitude, behavioural research, decision making, and energy policy. Notably, the second largest cluster (green) displayed technologies such as hydrogen and CCS, as well as quantitative methods including structural equation modelling (SEM) and regression analysis. Additionally, a smaller cluster (blue) isolated approaches outlined in Section 2.3 such as the TPB, TAM, and SETA framework

[1] Firstly, the following filters were applied to explore clusters: minimum number of keyword occurrences = 5 (320 met the threshold); minimum number of keyword occurrences = 10 (135 met the threshold); minimum number of keyword occurrences = 15 (80 met the threshold).

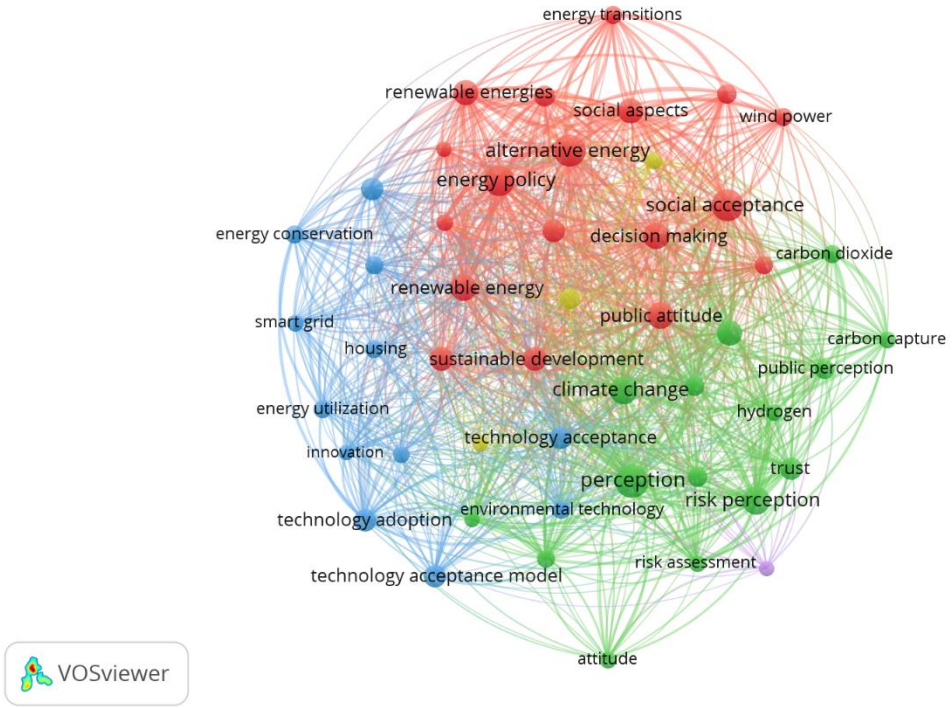

Fig. L-2. Network visualisation of connected keywords in dataset (N = 620).

National hydrogen strategies and hydrogen acceptance research

The following materials provide supporting evidence for the retrieved studies on hydrogen energy acceptance. Fig. L-3 shows the geographic distribution of studies. With the exception Taiwan (possibly due to political constraints), all countries within the dataset have national hydrogen strategies. The linkages between these two areas offers a fruitful avenue for future research on the growth of national hydrogen economies and prospects for social acceptance.

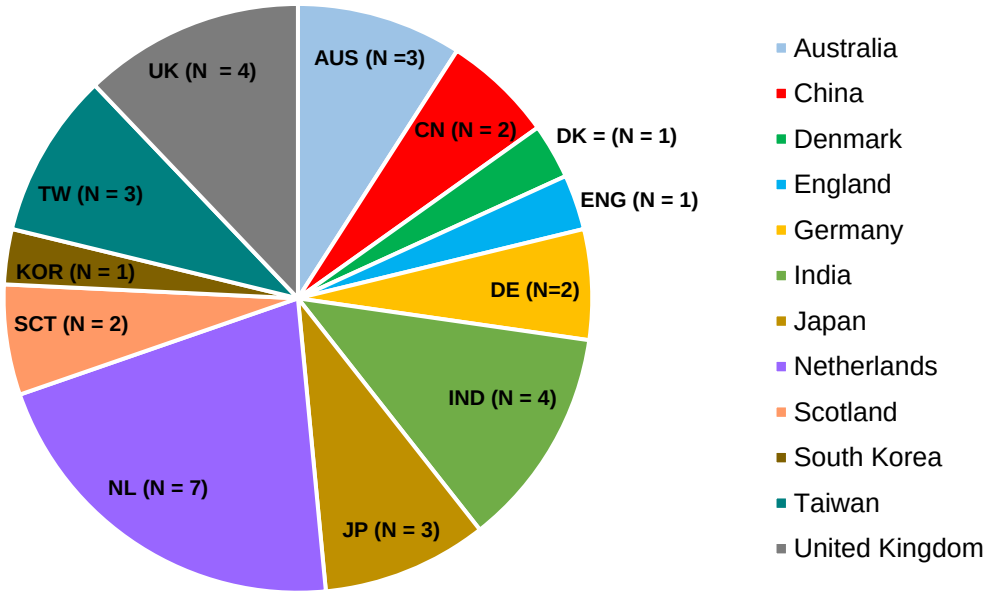

Fig. L-3. Geographic distribution of international studies on hydrogen energy acceptance (N = 33

Table L-6 reports the coding results for acceptance constructs identified for each study in the hydrogen dataset (N = 33), while Table L-7 reports the coding results for acceptance constructs identified for each study in the domestic energy dataset (N = 42).

Table L-6. Coding results for studies on hydrogen energy acceptance.

	ACCEPTANCE CONSTRUCT													
Study	**AWR**	**OK**	**SK**	**FP**	**ENV**	**TECH**	**PB**	**PC**	**PR**	**PE**	**NE**	**SP**	**ST**	**Total**
[1]							X	X		X	X		X	5
[2]	X				X	X	X	X	X	X	X	X		9
[3]	X		X		X	X	X		X	X	X			8
[4]					X									1
[5]					X		X		X				X	4
[6]					X		X	X	X	X	X		X	7
[7]	X	X	X		X		X	X	X	X	X		X	10
[8]		X	X	X	X		X		X			X	X	8
[9]	X					X	X		X					4
[10]	X	X	X		X			X	X			X	X	8
[11]		X		X	X	X			X					5
[12]	X				X	X			X			X	X	6
[13]	X		X				X	X	X			X	X	7
[14]	X	X			X		X		X	X	X	X		8
[15]					X		X	X	X	X	X		X	7
[16]				X	X	X	X	X	X			X		7
[17]						X			X			X		3
[18]	X		X	X		X						X		5
[19]		X	X		X	X		X	X			X	X	8
[20]					X		X							2
[21]	X	X	X	X	X		X	X	X	X	X	X	X	12
[22]	X		X	X	X	X	X	X	X		X	X		10
[23]	X		X		X	X	X	X	X					7
[24]			X	X	X		X					X	X	6

[25]				X	X		X		X	X	X	X	X	8
[26]			X	X	X	X	X	X	X			X	X	9
[27]	X		X	X	X	X	X		X			X	X	9
[28]	X				X	X	X	X	X			X		7
[29]	X		X		X		X	X		X			X	7
[30]	X		X	X	X	X	X	X	X	X		X	X	11
[31]				X	X									2
[32]				X	X								X	3
[33]				X	X	X	X	X	X				X	7
Total	16	7	15	14	28	16	24	17	25	11	10	18	19	**220 (M = 6.67)**

Table L-7. Coding results for studies on domestic energy acceptance.

	ACCEPTANCE CONSTRUCT													
Study	**AWR**	**OK**	**SK**	**FP**	**ENV**	**TECH**	**PB**	**PC**	**PR**	**PE**	**NE**	**SP**	**ST**	**Total**
[34]	X			X	X	X	X	X	X				X	8
[35]	X		X	X	X	X	X		X					7
[36]				X	X	X	X							4
[37]				X	X	X	X							4
[38]				X		X	X		X			X		5
[39]	X	X	X	X	X	X	X	X	X			X	X	11
[40]					X		X						X	3
[41]				X	X		X	X		X				5
[42]					X	X	X							3
[43]				X	X	X	X	X	X					6
[44]	X		X	X	X	X	X		X					7
[45]	X		X	X	X		X		X					6
[46]					X	X	X							3
[47]				X	X	X	X		X					5
[48]	X			X	X	X	X	X	X		X		X	9
[49]	X	X		X	X	X	X						X	7
[50]		X	X		X								X	4
[51]				X	X	X	X		X					5
[52]	X	X		X	X		X	X						6
[53]				X	X	X	X					X		5
[54]	X		X	X	X	X	X	X	X	X	X			10
[55]				X	X		X	X	X					5
[56]	X		X		X	X	X							5
[57]				X		X	X							3
[58]	X		X			X	X		X					5
[59]	X	X	X	X	X		X	X	X					8
[60]	X			X	X		X	X	X	X			X	8

[61]				X	X	X				X			X	5
[62]					X	X	X							3
[63]				X	X	X	X	X	X	X	X			8
[64]	X		X	X	X	X			X					6
[65]	X		X	X	X		X			X			X	7
[66]	X	X	X		X	X	X	X	X					8
[67]	X		X		X	X	X							5
[68]				X	X	X	X		X				X	6
[69]				X		X	X	X	X	X	X			7
[70]	X		X	X		X	X					X		6
[71]				X	X	X	X							4
[72]	X		X		X	X	X			X				6
[73]	X				X	X	X			X			X	6
[74]				X		X	X			X	X		X	6
[75]				X		X	X						X	4
Total	20	6	15	31	35	33	39	13	20	10	5	4	13	**244 (M = 5.81)**

Table L-8 reports the data for Fig. 2-17, showing the mean number of acceptance constructs operationalised within energy acceptance studies for the period 2017–2023, based on the retrieved studies.

Table L-8. Average number of technology acceptance constructs engaged across the sample annually for hydrogen and domestic energy studies.

Year	Hydrogen studies (N = 33)	Domestic energy studies (N = 42)	Full sample (N = 75)
2017	6.0	6.1	6.1
2018	5.5	4.8	5.1
2019	7.5	5.6	6.6
2020	5.7	6.3	6.0
2021	5.0	6.6	5.8
2022	8.8	5.3	7.0
2023	7.0	5.0	6.0

Visual comparison between the Sustainable Technology Acceptance Model and the unified theory of domestic hydrogen acceptance

Fig. L-4 and Fig. L-5 present the Sustainable Technology Acceptance (SETA) model and the unified theory of domestic hydrogen acceptance, respectively. The differences between the two frameworks are further highlighted in Table L-5.

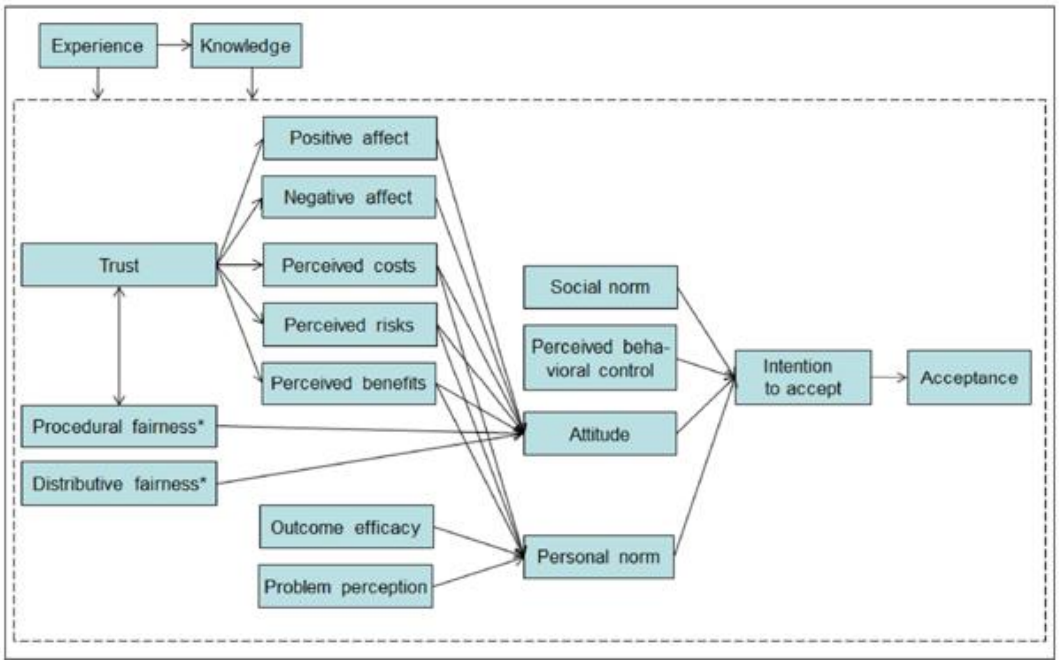

Fig. L-4.The Sustainable Technology Acceptance Model.

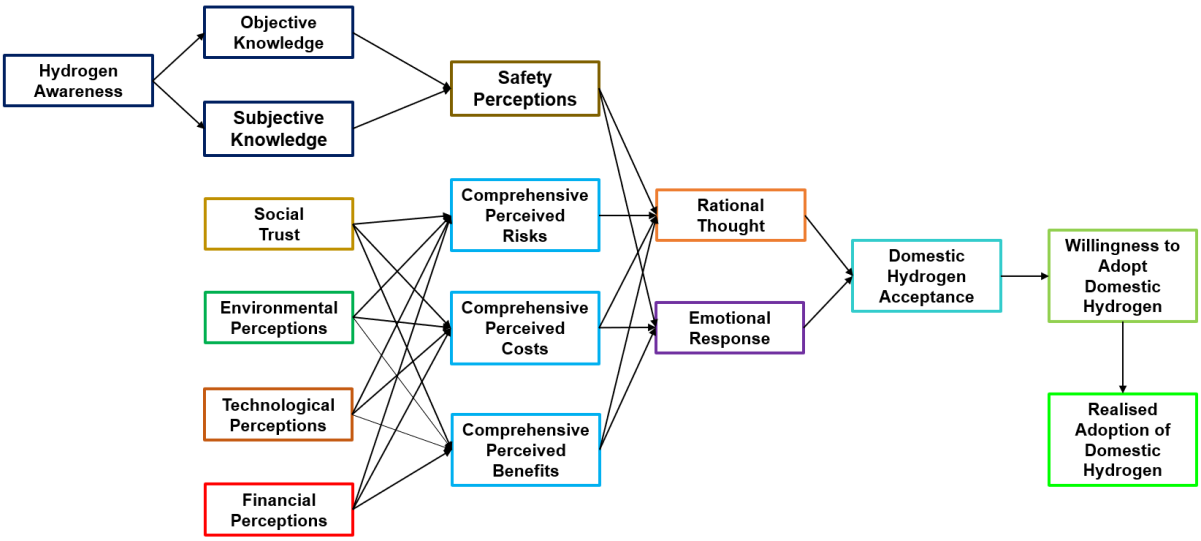

Fig. L-5. The unified theory of domestic hydrogen acceptance.

Insights from applications of structural equation modelling

SEM features consistently throughout this analysis, emerging within both the theoretical review in Section 2.3 and preceding sub-sections of the SLR (see Sections 2.4.1 and 2.4.2), alongside Fig 2-13 and Fig 2-14 (see Section 2.4.3.1). Reflecting on the use of SEM techniques offers additional insights into methodological approaches to examining technology acceptance.

At the outset, it is important to distinguish between the traditional method, CB-SEM, and PLS-SEM which is a more emergent yet well-established technique. In brief, the former method is a covariance-based technique suited to testing how well the data fits an already established theoretical model [80], whereas PLS-SEM is a variance-based approach which can serve as both an explorative and predictive method; suited to situations of high complexity where limited theory formation has been established [81]. SEM featured in approximately 45% of the reviewed studies (N = 34), with a somewhat stronger representation within domestic energy acceptance studies (N = 21, ~47%) compared to hydrogen acceptance studies (N = 13, ~39%). For the most part, the remaining studies employed a range of regression analysis techniques [82]. The observed trend likely reflects the more recent emergence of scholarship on hydrogen acceptance since the mid-2000s [83,84], whereas studies on rooftop solar PV adoption have evolved over the course of four decades [85–87].

To derive additional insights, Fig. L-6 presents SEM-based studies from across the dataset for the period 2014–2023. Consequently, the PLS-SEM study conducted by Kang and Park [3] in 2011 on HFCV acceptance in South Korea is omitted from the visualisation to improve readability. Additionally, it should be noted that studies represented in 2023 (N = 5) correspond to the Scopus search conducted in September, therefore several additional results are likely to be captured for the full year. A relatively clear pattern emerges from the comparative analysis, reflecting the increased uptake of PLS-SEM within the last few years. Specifically, close to all studies up until 2019 employed CB-SEM (N = 12) compared to PLS-SEM (N = 2), whereas this pattern has increasingly reversed since 2019 (CB-SEM = 6; PLS-SEM = 13). Moreover, nine out of ten of the studies sampled between 2022 and 2023 employed PLS-SEM, with a near equal split between hydrogen energy (N = 5) and domestic energy studies (N = 4).

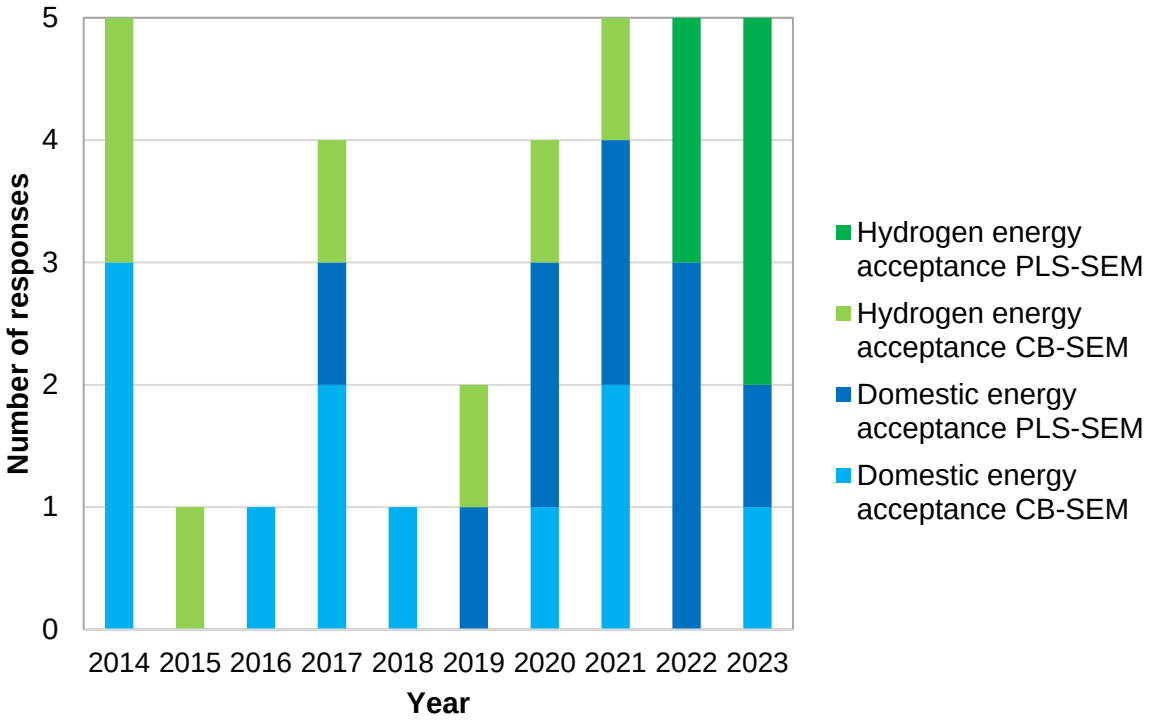

Fig. L-6. Application of structural equation modelling techniques across sample (N = 75).

While it is beyond the scope of this integrative, comparative review to debate the relative merits of SEM-based techniques [88–91], it may be inferred that Fig. L-6 reflects the need to further explore theories of low-carbon energy acceptance across the mix of technologies examined within this sample. Critically, this objective can be better supported via PLS-SEM [92]. Furthermore, the predominance of CB-SEM in earlier years potentially reflects the use of extended technology acceptance models during the period, including the SETA model in hydrogen studies. In such cases, acceptance constructs are well-established, and the focus may be more on theory confirmation, as opposed to theory development. Additionally, the decision to use either SEM technique may reflect trends in research developments and available software, as well as personal preferences among analysts.

On a final note, Sarstedt and colleagues [93] have pioneered recent advancements in SEM, including commentaries on the viability of available methods: “Our discussions show that researchers need to clearly distinguish between (conceptual) measurement approaches and the (statistical) estimation perspectives when judging the appropriateness of or choosing a specific SEM method.” However, to date, no study has comprehensively examined the application of SEM methods within the energy

acceptance literature, whereas such reviews are prominent in the field of business and management [94–96]. Future research can fill this knowledge gap by drawing on larger sample of SEM-based energy acceptance studies to understand ‘where the bias lies’ [93] among energy acceptance scholars, and whether trends reflected in Fig. L-6 can be substantiated.

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APPENDIX M. Exploring the contours of consumer heterogeneity: Towards a typology of domestic hydrogen acceptance (chapter 3)

Developments in national hydrogen strategies

In June 2023, the US Department of Energy formalised its national hydrogen strategy [1] following a draft version in September 2022 [2]. The US government has allocated $8 billion towards developing Regional Clean Hydrogen Hubs, alongside $1 billion for implementing a Clean Hydrogen Electrolysis Program, among other investments [3].The Australian Government has responded with plans to review its national hydrogen strategy [4], while several countries such as Canada [5] and EU Member States [6] are set to follow suit, as the global hydrogen landscape rapidly evolves [7–9]. To date, multiple studies conducted across a wide range of countries such as Canada [10,11], China [12,13], South Korea [14], Germany [15] and Poland [16] have examined the feasibility of scaling up different hydrogen energy systems [17]. Notably, the US hydrogen strategy focuses predominantly on industrial applications and some aspects of the transport sector such as medium and heavy-duty vehicles, maritime applications and ports, as well as aviation [1].

Findings from literature review

Kar et al. [18] found that since 2015, in addition to more generic keywords referencing the ‘hydrogen economy’ (N = 299) and ‘hydrogen’ (N = 291), articles have focused on supply-side aspects, technological efficiency, and environmental impacts, whereas consumer-orientated research and a demand-side focus remain scarce: ‘hydrogen fuels’ (N = 223), ‘hydrogen production’ (N = 190), ‘hydrogen storage’ (N = 133), ‘fuel cells’ (N = 110), ‘fuel economy’ (N = 79), ‘carbon dioxide’ (N =64), ‘electrolysis’ (N = 55), ‘electrocatalysis’ (N = 54) etc. [18]. The dominance of techno-economic studies in the hydrogen literature [19–21] resonates with the lack of funding allocated towards climate-related social science research [22]. The status quo has motivated calls for stronger investment in social sciences and humanities (SSH) research on the energy transition [23,24], which includes the growing domain of the hydrogen economy.

The most commonly cited sub-factor across the sample was environmental knowledge (N = 15), while technology and environmental attitude (N = 7) further contributed to the environmental awareness category, whereas perceived cost or risks (i.e. economic

beliefs) featured in 11 studies. Excluding demographic sub-factors (N = 53), environmental awareness was the most frequently cited category (N = 24), followed closely by economic benefits (N = 23). By contrast, the remaining categories featured in 11 (infrastructure construction), 9 (social influence, psychological needs), and 7 studies (government policies). Furthermore, the study [25] suggests that trust in government and industry (N = 5), distributive benefits (N = 6), perceived benefits and lifestyle fit (N = 5), and social equity (N = 1) remain underexplored factors in the hydrogen acceptance literature.

Due to the relatively small number of available quantitative studies on hydrogen acceptance, the demarcation applied by Scovell [87] returned several tied ranks, which makes it difficult to distinguish between factors. For example, awareness, objective knowledge, and social trust were cited in six studies (tied rank 5th), while perceived effects, experience, and fairness featured in three studies (tied rank 6th). Nevertheless, the top two factors (perceived benefit/value/usefulness and problem perception/awareness) were cited in 10 studies, whereas the bottom three factors (perceived costs, affect, and personal norm) appeared in only two studies, thereby reflecting a clearer degree of differentiation.

Interestingly, at the level of behavioural acceptance [26], Gordon et al. [27] categorised the lived experience of cooking ranked as a major factor, whereas the lived experience of cooking represented a minor factor, in view of the more present socio-material reality of gas hobs compared to boilers [28]. However, the observed divergence also reflects one of the limitations of the narrative review [27], wherein supporting evidence for this argument relied on just three studies [28–30]. By contrast, both critical factors – financial costs, and knowledge and awareness – were derived based on evidence from more than 10 studies.

Following 10 focus groups conducted with UK participants between February and April 2022, Gordon et al. examined consumer perceptions of hydrogen homes appliances [31], hydrogen production pathways and the UK hydrogen strategy [32], in addition to market dynamics, stakeholder trust, disruptive impacts, and perceived risks, costs, and benefits [33]. Consequently, the research group [31–33] succeeded in analysing a wide range of previously identified factors through mixed-methods data analysis (i.e. qualitative data and poll data. Table M-1 further summarises the literature findings.

Hydrogen acceptance findings in the UK and Australia

Table M-1. Summary of findings on themes and categories of hydrogen acceptance.

Study	Country context and sample size	Focus of study and methodology	Identified themes or categories of hydrogen technology acceptance	Key findings
[34]	• South Australia and Victoria • N = 1824	• Public willingness to make trade-offs in supporting the development of a national hydrogen industry • Fractional multinomial logistic regression	• Safety • Climate change mitigation • Affordability • Reliability • Accessibility • Job creation	• Safety was the most important factor influencing willingness to support a hydrogen industry, followed by climate change mitigation, affordability, reliability, accessibility, and job creation • Respondents were more likely to assign importance to factors addressing concerns or providing benefits • Socio-demographic (e.g. age, location) and attitudinal characteristics (e.g. concern about climate change, hydrogen knowledge) influenced consumer perceptions of hydrogen industry characteristics
[35]	• Australia • N = 906[a]	• Social acceptance of hydrogen for national use (including a focus on domestic heating and cooking) and export applications • Multivariate regression analysis	• *Affect* • *Trust* • *Perceived risk* • *Safety* • Support *to free-market* • Perceived *benefits* and *costs* • Socio-demographic variables[b]	• Support for domestic hydrogen is associated with recognition of climate protection benefits and health benefits (i.e. no carbon monoxide emissions) • Support correlates to technology engagement (i.e. propensity to be an early adopter or self-perception as an 'innovator'), whereas opposition to domestic hydrogen is associated with the level of perceived inconvenience (i.e. disruptive impacts) of the switchover
[36]	• Australia • N = 3020	• Public support for export and domestic applications of hydrogen	• **N/A** (measures the effect of information provision on subjective support for domestic hydrogen and hydrogen for export)	• Information provision (i.e. a short video, images, and text descriptions) increased support for hydrogen by 10% when considering export applications and 9% in relation to national use

		• Ordinary least squares regression analysis • Ordered logistic regression analysis		• Natural gas users, residents living in metropolitan areas, owners of solar PV, and consumers self-identifying as early adopters of new technologies are more likely to increase their support for hydrogen following exposure to information provision
[37]	Australia (Brisbane, Queensland) N = ~28 (Four groups with 6–8 participants)	• Public perceptions of hydrogen energy technologies across the supply chain • In-person focus groups • Reflexive thematic analysis	• Uncertainty and unproven technologies • Safety and risk perceptions • Economic opportunities (nationally and locally) • Inefficiency and cost • Environmental impacts • Energy security; Hydrogen competing with other renewables • Water use	• Uncertainty over the feasibility of hydrogen contributed towards negative perceptions of safety, and lack of perceived benefits • Most participants supported the use of renewable energy sources for hydrogen production, but believed that hydrogen produced from natural gas with carbon capture and storage (CCs) should play a role in the medium term • Generally low levels of support for using hydrogen for household heating compared to industrial and heavy transport applications
[31]	• United Kingdom • N = 58	• Examines consumer perceptions of hydrogen home appliances and low-carbon technologies for domestic heating and cooking • Online focus groups	• Controllability and ease of use • Safety • Convenience • Efficiency and responsiveness • Familiarity • Reliability • Space savings • Cost effectiveness • Space savings • Quiet performance • Access to skilled personnel • Cleaning and maintenance • Environmental impacts • Aesthetics	• Existing gas users are somewhat open to the idea of adopting hydrogen appliances, but have divergent views towards boilers and hobs • Safety assurances are particularly important for fuel poor households with young families • Hydrogen heating may gain consumer acceptance is appliances are efficient, reliable, convenient, smart, and environmentally-friendly • The modernness, safety and aesthetics of induction hobs appear more favoured compared to gas cooking when considering current and future technology preferences
[32]	• United Kingdom	• Examines consumer perceptions of	• Knowledge and awareness • Information (preferences)	• Males have a higher level of subjective hydrogen knowledge (M = 2.00) compared to

	• N = 58	hydrogen production pathways and the UK Hydrogen Strategy • Online focus groups	• Production perceptions (blue and green hydrogen) • Environmental benefits • Energy and environmental justice • Disruptive impacts • Energy efficiency • Financial factors • Social trust	females (M = 1.56), as a measured on a four-Point Likert scale • Respondents expressed stronger support for 'green' (renewable-based) hydrogen compared to 'blue' hydrogen production (i.e. reliant on natural gas and carbon capture and storage) • 39% and 46% of respondents were *very supportive* and *somewhat* supportive of the twin-track production strategy
[33]	• United Kingdom • N = 58	• Examines consumer perceptions of market dynamics, stakeholder trust, disruptive impacts, and perceived risks, costs, and benefits associated with the domestic hydrogen transition • Online focus groups	• Public trust (government, energy sector, and research and development) • Financial perceptions • Consumer engagement with energy markets • Technology perceptions and preferences • community benefits, costs, and risks • Spatial and equity impacts • Disruptive impacts • Individual risks and energy vulnerabilities	• Market competition, appliance choice, affordable prices, and social fairness emerged as important drivers of consumer acceptance • Trust deficits in the UK government and energy sector may undermine the prospect of deploying hydrogen homes at scale • Financial security is a stronger motivational driver than perceived environmental benefits • Hydrogen homes are perceived as a potentially positive mechanism for industrial regeneration and local economic development • Households anticipate the short-term disruptive impacts of the switchover to be tolerable

[a] The main survey has a larger sample size (N = 2785) compared to the sub-sample on domestic hydrogen applications.
[b] *Levels of education; belief in global warming; values/beliefs/norms scale; free market with environmental considerations; trust in government; trust in industry; and household energy source.*

Sub-factors of domestic hydrogen acceptance

Table M-2. Definition of sub-factors of domestic hydrogen acceptance.

Core factor	Sub-factor	Response type
Information	• *Pro information about domestic hydrogen in general*	• Responses affirming the need for more general information on domestic hydrogen
	• *Knowledge deficit*	• Responses citing an expressed lack of knowledge and awareness regarding the domestic hydrogen transition or hydrogen fuel in general
	• *Pro information about hydrogen costs*	• Responses affirming the need for specific information on financial costs related to the domestic hydrogen transition
	• *Pro information about hydrogen safety*	• Responses affirming the need for specific information on safety implications of the domestic hydrogen transition
Image	• *Fuel of the future*	• Responses citing positive prospects for hydrogen in the long-term, often referring to its definitive role as a future fuel
	• *Pro hydrogen concept*	• Responses citing the positive value of hydrogen as a general concept for potentially supporting the energy transition
	• *Town gas experience*	• Responses citing the town gas transition as an exemplar for transitioning to hydrogen homes
	• *Unpublicised status of hydrogen*	• Responses expressing concern over the lack of publicity and media coverage on hydrogen, which may infer a lack of value
	• *Negative social representation*	• Negative impressions of hydrogen fuel due to historical associations or public imagery
Finance	• *Financial benefits*	• Responses citing expectations for financial benefits from switching to domestic hydrogen appliances
	• *Financial risks*	• Responses citing the potential of increased financial benefits from switching to domestic hydrogen appliances
	• *Conditional on financial implications*	• Responses conveying the notion that forming a positive or negative attitude towards domestic hydrogen is contingent on financial implications, which were currently perceived to be indeterminate
	• *Boiler rejection due to recent investment*	• Responses rejecting the domestic hydrogen transition on grounds of recently purchasing a new gas boiler
Affect	• *Positive emotions*	• Responses expressing a positive or range of positive feelings associated with the domestic hydrogen transition
	• *Negative emotions*	• Responses expressing a negative or range of negative feelings associated with the domestic hydrogen transition
Environment	• *Environmental benefits*	• Responses citing the prospect of benefits to the environment such as reducing carbon emissions
	• *Environmental risks*	• Responses citing potential risks to the environment such as carbon lock-in
	• *Net-zero scepticism*	• Responses expressing scepticism in the government's net-zero agenda and therefore

		opposing the phase-out of natural gas appliances for hydrogen appliances
	• *Conditional on environmental implications*	• Responses conveying the notion that forming a positive or negative attitude towards domestic hydrogen is contingent on environmental implications, which were currently perceived to be indeterminate
Fairness and equity	• *Choice deficit*	• Responses taking issue with the potential lack of choice involved in converting to a hydrogen home
	• *Trust deficit*	• Responses citing a lack of consumer trust in the stakeholders involved in the domestic hydrogen transition such as the government
	• *Profit motives of energy companies*	• Responses opposing the domestic hydrogen transition due the perceived vested interest and profit motives of energy companies
	• *Consumers shouldn't pay for the costs of the domestic hydrogen transition*	• Responses objecting to passing on the costs of the domestic hydrogen transition to households
	• *Government should pay the costs of the domestic hydrogen transition*	• Responses suggesting that the UK government should cover or contribute significantly towards the costs of the domestic hydrogen transition, as opposed to consumers
	• *Energy companies should pay the costs of the domestic hydrogen transition*	• Responses suggesting that energy companies should cover or contribute significantly towards the costs of the domestic hydrogen transition, as opposed to consumers
	• *Distributional injustice (general)*	• Responses flagging general risks of social unfairness and inequity, without citing a specific sub-factor identified within this category
Technology	• *Pro technology or modern progress*	• Responses advocating for the domestic hydrogen transition as a mechanism for advancing society and technological progress
	• *Pro Research & Development for hydrogen*	• Responses supporting the need for more investment in R&D activities to support the domestic hydrogen transition
	• *Pro alternative low-carbon options (not hydrogen)*	• Responses opposing the hydrogen transition in favour of other low-carbon energy sources and technologies
	• *Risk aversion to new technologies*	• Responses expressing aversion to hydrogen due to its status as an emerging energy technology in the domestic context
	• *Hydrogen perceived as an unproven technology*	• Responses opposing domestic hydrogen appliances on the grounds that the technology remains unproven
Safety	• *Safety benefits*	• Responses citing potential safety benefits from the deployment of hydrogen home appliances
	• *Safety risks*	• Responses citing potential safety risks from the deployment of hydrogen home appliances
	• *Conditional on safety implications*	• Responses conveying the notion that forming a positive or negative attitude towards domestic hydrogen is contingent on

		safety implications, which were currently perceived to be indeterminate
Economy	• *Economic benefits*	• Responses citing the likelihood of economic benefits for wider society due to the domestic hydrogen transition
	• *Economic risks*	• Responses citing the likelihood of economic risks for wider society due to the domestic hydrogen transition
	• *Energy security benefits*	• Responses citing the likelihood of energy security benefits for wider society due to the domestic hydrogen transition
	• *Energy security risks*	• Responses citing the likelihood of energy security risks for wider society due to the domestic hydrogen transition
	• *Conditional on cost-of-living crisis*	• Responses conveying the notion that forming a positive or negative attitude towards domestic hydrogen is contingent on impacts to the cost-of-living crisis, which were currently perceived to be indeterminate
Logistics	• *Age barrier*	• Responses rejecting the domestic hydrogen transition since it is unlikely to occur within their lifetime
	• *Disruptive impacts*	• Responses flagging issues related to the potential short-term disruptive impacts of the domestic hydrogen transition
	• *Logistical risks*	• Responses citing logistical risks associated with the domestic hydrogen transition
Social	• *Community benefits*	• Responses expressing expectations for community benefits due to the domestic hydrogen transition
	• *Societal benefits*	• Responses expressing expectations for social benefits due to the domestic hydrogen transition
	• *Societal risks*	• Responses expressing concern over potential social risks due to the domestic hydrogen transition
	• *Conditional on societal implications*	• Responses conveying the notion that forming a positive or negative attitude towards domestic hydrogen is contingent on societal implications, which were currently perceived to be indeterminate
Performance	• *Efficiency or utility benefits*	• Responses citing expectations for improvements in terms of appliance performance following a conversion to hydrogen boilers and hobs
	• *Efficiency or utility losses*	• Responses citing concerns over negative impacts to appliance performance following a conversion to hydrogen boilers and hobs

Iterations of hybrid deductive-inductive coding

The data analysis procedure involved several stages and multiple iterations as discussed in Section 3.3.4. Initially, all available responses were used (N = 1213) before filtering down the valid responses (N = 1064), which led to a preliminary assessment as illustrated in Fig. M-1 and Fig. M-2.

Notably, the information core factor returned a higher frequency, while initially the ***image*** category was labelled as ***future fuel***, among other differences. The change was justified following the retrieval of *negative social representation* as a negative tertiary sub-factor, which composed the image category. Furthermore, as shown in Fig. M-2, the initial coding procedure resulted in a primary, secondary, and tertiary category of core acceptance factors, as opposed to just two categories (see Fig. 3-4 and Fig. 3-5). However, the tertiary category had a higher weighting than the secondary category, which led to a sub-optimal distribution. By contrast, through binary coding in the main analysis, the three categories were retained with a corresponding reduction between primary, secondary, and tertiary categories (see Fig. 3-6). As an illustrative example of the iterative process of qualitative coding, the results shown here provided the initial template, prior to reducing the sample size and further refining the results through cross-checks as well as binary coding.

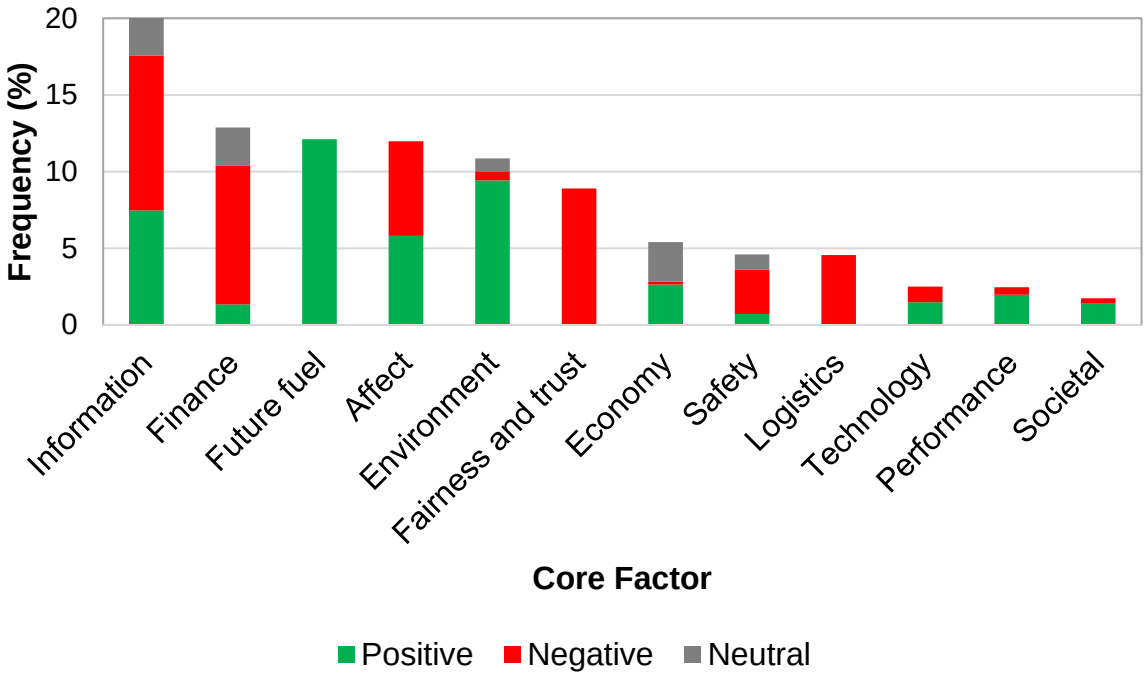

Fig. M-1. Breakdown of core factors of domestic hydrogen acceptance (full counting: N = 1235).

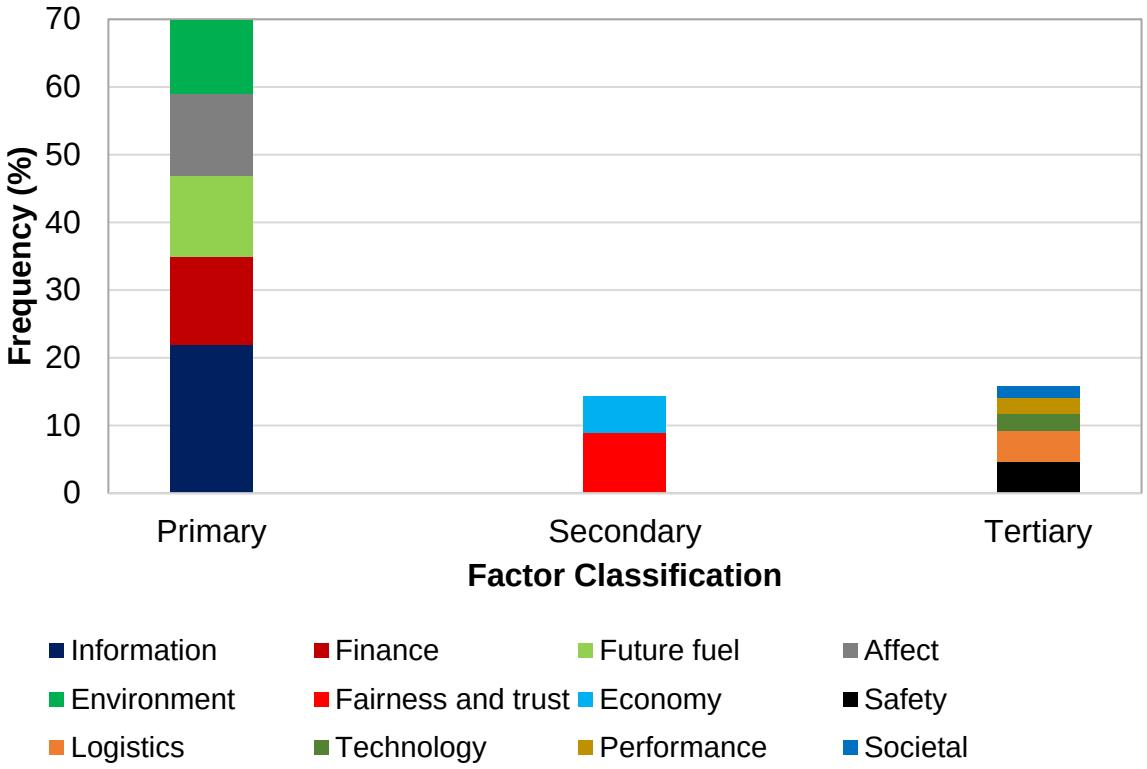

Fig. M-2. Breakdown of core factors of domestic hydrogen acceptance by category (full counting: N = 1235).

Neutral sub-factors of domestic hydrogen acceptance

Following the proposed hydrogen acceptance typology, neutral secondary sub-factors consisted of *conditional on financial implications* (finance), *conditional on environmental implications* (environment), *conditional on the cost-of-living crisis* (economy) and *conditional on safety factors* (safety).

Highlighting a case of financial contingency and reservations, one respondent conveyed a pragmatic attitude which may be deeply entrenched across much of society, "*It will all depend on the cost to consumers – most people are driven by price and hence will not adopt this technology; if to do so will mean that they are out of pocket as a result*" (MEG 201). It follows that the capabilities of boiler manufacturers to deliver on 'price promises' [38], alongside parallel 'price pledges' from government and energy suppliers [33], will configure the emerging contours of the domestic hydrogen acceptance matrix [39]. Another respondent remarked, "*I'm all for this, as long as it's not too much more expensive and doesn't increase fuel poverty*" (BLG 186).

Specifically, respondents perceived the cost-of-living crisis as a stimulus for action, or conversely as a disincentive and risk barrier, with such perspectives sometimes contingent on more information and proof-of-concept. Capturing several perspectives, one respondent framed their view as follows:

> "*It looks good but whether it really makes a difference is something to be seen. With the current energy crisis, perhaps this is the way forward. But with the cost-of-living crisis, if it is expensive, how will people afford it? They may then be reluctant to switch. I doubt it would be cheap. It needs to be proven to convince everyone and needs to be affordable*" (MEG 189).

Alternatively, other respondents prioritised safety aspects alongside cost factors:

> "*It sounds like a great solution to some of our energy problems. My only concern currently is to learn more about the safety of hydrogen. If it is just as safe as natural gas, then I feel a lot should be invested into this source of energy and its development. Also provided that it will ultimately be around as cheap as fossil fuels*" (BLG 233).

Additionally, some comments engaged more specifically with hydrogen appliances, for example, "*I think if it becomes safer by adding an odourant and colouring, then I would be up to installing hydrogen hobs and boilers"* (BLG 126).

Similarly, respondents noted environmental aspects within the broader discussion of other factors: "*seems an interesting area and whilst been around for a while, we are still in early stages of rolling out. If it makes us greener then has to be a positive, as long as costs are no greater than now*" (MEG 244), and "*anything that helps reduce global warming is fine with me, as long as the measures are safe and cost effective*" (MEG 6).

Table M-3 consolidates the assessment of neutral secondary sub-factors by reporting a comprehensive account of consumer responses, which in many instances cut across more than one acceptance factor. We conclude this part of the analysis by reviewing tertiary sub-factors in the next section.

Table M-3. Responses conditional on financial, environmental, and safety implications.

Respondent ID	Illustrative quotations
BLG 78	• *I don't fully understand it but if it is good for the planet and safe for people then I think it will be a good thing in the long term.*
BLG 107	• *I haven't heard of it before but would be very willing to try it if it is affordable, safe and better for the environment. I have wondered what will replace fossil fuels.*
BLG 116	• *I need to know more about the safety and the likely cost of hydrogen before I could endorse it fully.*
BLG 129	• *I think it has good potential to solve our energy crisis, however, a lot more information needs to be made available about it for logistic purposes.*
BLG 179	• *If it's sustainable and cheaper would be happy to switch.*
MEG 70	• *I currently have solar panels and use an induction hob, so hydrogen would have to be significantly cheaper to make me convert to a hydrogen hob. I would be interested in a hydrogen boiler.*
MEG 152	• *I'm very optimistic about the use of hydrogen. A lot would depend on how much the energy bills would be, before I decided about it.*
MEG 161	• *If it proved to be good for the environment and the initial start-up cost is reasonable, the country should go for it.*
MEG 162	• *If it's good for the environment and doesn't impact too much financially then I am supportive.*
MEG 267	• *We are in an economic crisis. We have to make the environmental costs more towards who earn more, without causing this world into poverty.*
VEG 31	• *Good idea if it creates jobs and reduces fuel poverty.*
VEG 119	• *I would like to see if the impact is a contribution to cheap fuel and the environment.*
VEG 109	• *I would welcome the change if it's cheaper and it helps the environment.*
VEG 176	• *Safety is key. If produced from renewable electricity sources only, I'm in favour.*
FSG 34	• *I am happy to hear about hydrogen energy, and if it has a good impact on environment and is cheaper than the energy at present, I am fully supportive.*
FSG 97	• *I would be open to trying this, but the price has to be right and safe.*
FSG 109	• *If it saves money and is safe for environment, then why not.*
FSG 112	• *If safe and good for the environment, I think it can only be a good thing.*
FSG 127	• *It is an interesting technology, but safety and performance and costs will determine its success.*
FSG 143	• *I would be concerned initially, but if it proved to be safe and cost effective, I would consider it.*

Tertiary sub-factors of domestic hydrogen acceptance

Notably, respondents focused mostly on the *unpublicised status of hydrogen fuel* and the *profit motives of energy companies*. In some cases, respondents called for more information campaigns from the government and better media coverage to support the hydrogen switchover: "*there needs to be more public* awareness *by the government and media – if the media can actually say something positive for a change*" (VEG 188). Partly mirroring this perspective, one respondent remarked that "...*the media portrayal of hydrogen is poor*" (MEG 130). In other cases, consumers expressed scepticism over a perceived a lack of information dissemination in the mainstream media: "*not seen anything in the media, so unsure it will happen anytime soon*" (BLG 268).

The profit motives of energy companies [40] is an increasingly polemic issue [41,42], given the cost-of-living crisis [43,44], and recent economic climate in the UK [45,46]. Several participants engaged with this aspect of renewable energy acceptance (see Table 3-9), with some observations linking directly to the role of government: "*the government should be paying for most of this swap over, as well as energy companies. This is due to the massive profits that these companies make, and no doubt will continue to make*" (BLG 324); and "…*want government and industry to get off their backsides and provide households with green solutions. Make the roll out better planned and moderated than solar panels please*" (VEG 197).

Some survey participants also expressed a sense of *risk aversion* to hydrogen technologies. For example, one respondent stated, "*I'll wait to see how it affects others first*" (BLG 184), while another echoed this position, "*I'm very on the line and would need to do a lot more research before completely committing to anything irreversible*" (MEG 164). Concerns were also expressed over the potential *disruptive impacts* of the hydrogen switchover, with most comments attributed to respondents in the BLG. For example, one participant cited personal experience, "*I just don't trust engineers, as I had a leak before and it broke my meter. I don't want people in my house*" (BLG 109).

Within the tertiary category (see Section 3.4.5), several sub-factors were also identified which could prove more prevalent across parts of the UK population, depending on relevant socio-structural and contextual factors [27]. For example, a small fraction of the sample described an overtly *negative social representation*

associated with hydrogen due to historical events, while others lamented that they would fail to enjoy any benefits from hydrogen within their lifetime. Given that the oldest age group was 55+, it is plausible that a stricter age bracket (i.e. 70+) may have increased the frequency of such perspectives. Conversely, it is feasible that older citizens may anticipant minimal disruption following experience with the conversion from town gas to natural gas, which took place between the 1967 and 1977 [47]:

> *You will still be using the same distribution network pipeline. You won't have to change that, it will just be like when we went from coal gas to natural gas, most of the old pipeline has been renewed now* (MEG 254).

Another respondent from the BLG supported this viewpoint, "…*experienced the changeover from town gas to natural gas years ago. That went smoothly, so not worried about a further change.*"[1] It follows that consumer attitudes may be influenced by a combination of awareness regarding the historical switch to natural gas [48,49] and the ongoing Iron Mains Replacement Programme (IMRP) [50,51], which has the co-benefit of making the gas grid compatible for hydrogen (i.e. reducing the embrittlement problem) [47].

Another noteworthy tertiary sub-factor is *boiler rejection due to recent investment*, with consumers expecting their recently purchased boilers to last through until at least the next decade. One respondent made their view clear, "*I've just replaced my gas boiler. Why would I want to spend thousands again replacing it with hydrogen*?" (BLG 173). Other participants concurred with this position, "…*we have not long ago installed a new boiler and I would expect this to last us past 2030*" (MEG 79), and "…*I did just get a new gas boiler, so won't be changing for some time*" (FSG 156).

Rejecting the domestic hydrogen transition on grounds of recent boiler installation (or related investments in household energy technologies and efficiency measures) may affect a significant portion of society. Notably, around 1.7 million gas boilers were sold in 2019 to UK customers [52], which is equivalent to 7% of gas-grid connected homes [53]. Furthermore, *scepticism towards net zero* may prove more widespread among consumers without expressed interest in environmental issues and RETs. Disengagement with these areas, which may otherwise manifest in a lack of motivation

[1] This respondent was excluded from the final dataset due to instances of straight-lining in their quantitative responses, however, the qualitative statement is instructive as supporting evidence.

to change energy supplier [33,54], could derail the potential deployment of hydrogen appliances, as well as other low-carbon alternatives such as heat pumps [55–57].

Interestingly, both the BLG and VEG are relatively balanced in terms of acknowledging the need for both the government and energy companies to cover the costs of the transition; or to at least minimise the financial burden on consumers, which is particularly emphasised among the BLG, alongside the FSG. Nevertheless, with the exception of *consumers shouldn't pay for the costs of domestic hydrogen* (N = 32), which ranked 23rd in terms of predicting heterogeneity (ρ = 0.199), all other items displayed in Fig. 3-14 are tertiary sub-factors, which makes statistical inferences less tangible due to the limited sample size.

Beyond these areas, survey responses also highlight the importance of broader economic factors such as potential *energy security benefits*, which link to the *cost-of-living crisis*. Notably, at the tertiary level, *economic benefits* (N = 21) is also a significant predictor of group differences (ρ<0.001), which corroborates the analysis around energy security benefits in Section 3.4.6.2. Among the tertiary group, six additional sub-factors are statistically significant at different levels, as reported in Table M-4, disruptive impacts (ρ = 0.038); pro-alternative low-carbon options (ρ = 0.021); risk aversion to new technologies (ρ = 0.009); hydrogen perceived as an unproven technology (ρ = 0.027); conditional on societal implications (ρ = 0.063); and *unpublicised status of hydrogen* (ρ = 0.076).

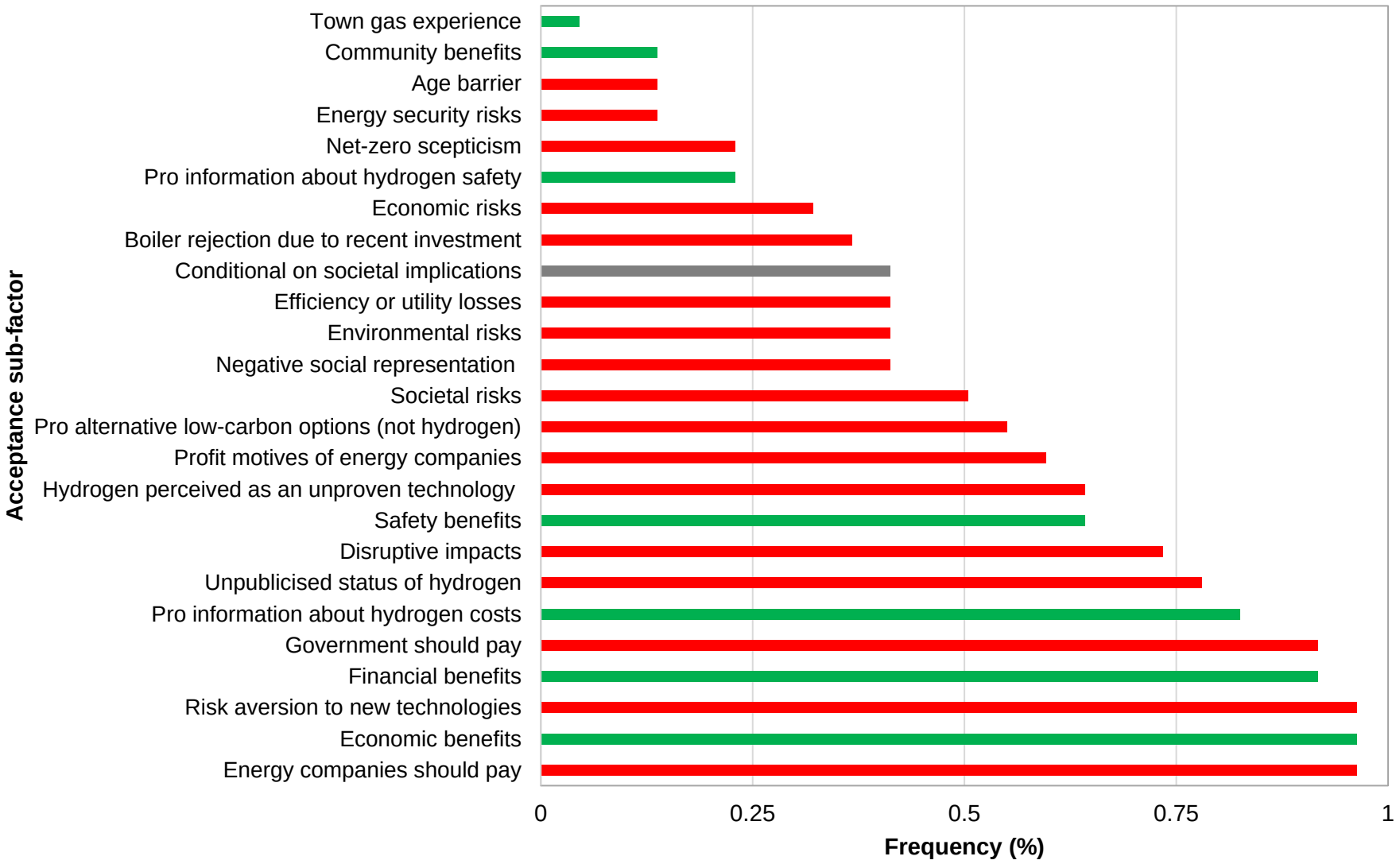

Fig. M-3. Tertiary sub-factors of domestic hydrogen acceptance.

In Table M-4, the nine acceptance sub-factors discussed in Section 3.4.6 are highlighted in **bold**. Tertiary sub-factors explaining consumer heterogeneity are highlighted in ***bold italics*** (N = 8).

Table M-4. Statistical results for differences across the sample regarding sub-factors of domestic hydrogen acceptance.

Core factor	Acceptance sub-factor	*p*-value
Information	Pro information about domestic hydrogen in general	0.556
	Knowledge deficit	**<.001*** **
	Pro information about hydrogen costs	0.565
	Pro information about hydrogen safety	0.530
Image	Fuel of the future	0.105
	Pro hydrogen concept	0.807
	Town gas experience	0.412
	Unpublicised status of hydrogen	**0.076***
	Negative social representation	0.626
Finance	Financial benefits	0.120
	Financial risks	**<.001*** **
	Conditional on financial implications	0.688
	Boiler rejection due to recent investment	0.533
Affect	**Positive emotions**	**0.083***
	Negative emotions	**0.065***
Environment	**Environmental benefits**	**<.001*** **
	Environmental risks	0.433
	Net-zero scepticism	0.583
	Conditional on environmental implications	0.199
Fairness and equity	**Choice deficit**	**0.012** **
	Trust deficit	0.770
	Profit motives of energy companies	0.413
	Consumers shouldn't pay for the costs of the transition	0.199
	Government should pay	0.509
	Energy companies should pay	0.519
	Distributional injustice (general)	**0.044** **
Economy	***Economic benefits***	**<.001*** **
	Economic risks	0.319
	Energy security benefits	**0.051**
	Energy security risks	0.466
	Conditional on the cost-of-living crisis	**0.016** **
Safety	***Safety benefits***	**0.061***
	Safety risks	0.129
	Conditional on safety implications	0.247
Logistics	Age barrier	0.466
	Disruptive impacts	**0.038** **
	Logistical risks	0.240
Technology	Pro technology or modern progress	0.712
	Pro Research & Development for hydrogen	0.544
	Pro alternative low-carbon options (not hydrogen)	**0.021** **
	Risk aversion to new technologies	**0.009*** **

	Hydrogen perceived as an unproven technology	**0.027****
Performance	Efficiency or utility benefits	0.294
	Efficiency or utility losses	0.890
Social	Community benefits	0.274
	Societal benefits	0.096
	Societal risks	0.643
	Conditional on societal implications	**0.063***

******* Statistically significant at the 1% level.
****** Statistically significant at the 5% level.
***** Statistically significant at the 10% level.

Analysis of consumer heterogeneity

Taken together, the MEG and VEG accounted for 63% of total responses referencing *environmental benefits* (see Fig. 3-12 and Fig. 3-13). It is noteworthy that the MEG attributed more importance to *environmental benefits* than the VEG, implying that even moderate levels of technology and environmental engagement are sufficient to raise awareness around hydrogen's clean energy credentials. However, different degrees of environmental engagement between the MEG and VEG did not translate into statistically significant differences between the two groups. By contrast, there was some divergence between the FSG and BLG, with the former group discussing environmental benefits almost twice as frequently as the latter.

It follows that *environmental benefits* are not only on the radar of citizens more directly engaged with issues of climate change and more familiar with RETs, but also resonate with consumers experiencing fuel stress. Nevertheless, given the response of the BLG, it can be concluded that greater public awareness concerning the potential benefits of the domestic hydrogen is needed to strengthen conditions for social acceptance.

Regarding the observed *knowledge deficit* concerning domestic hydrogen, the VEG had the lowest knowledge deficit (*Md* = 474), followed by the FSG (*Md* = 513), the MEG (*Md* = 539), and the BLG (*Md* = 572). In this respect, it was somewhat surprising that the MEG was more equivalent to the FSG and the BLG, as opposed to the VEG. The analysis suggests that moderate levels of environmental and technology engagement may not necessarily signify more knowledge about hydrogen when compared to other groups who are not very engaged in these areas.

Notably, this discrepancy makes *knowledge deficit* a significantly more heterogeneous sub-factor than its positive counterpart, *pro hydrogen information* which ranked 16th (ρ = 0.556). It follows that group differences, as constructed through the sampling approach (see Section 3.3.2), are a significant indicator of corresponding hydrogen knowledge levels, whereas the general preference or demand for more information about hydrogen is relatively homogenous across different consumer segments.

In view of the trends reported for *financial risks*, it may be inferred that environmentally and technology engaged respondents have a tendency towards greater economic security compared to not only fuel stressed respondents, which it to be somewhat

anticipated, but also in relation to respondents above the fuel stress line. Moreover, this finding affirms the need to examine the extent to which key socio-structural variables such as income and housing tenure may potentially counteract concerns over financial risk [27,58,59]. In response, subsequent research efforts should aim to establish the mechanisms underlying observed levels of consumer heterogeneity in relation to financial risks.

Meanwhile, it is probable that concerns over a lack of choice among the FSG, and to a lesser extent the BLG, emanate from worries related to financial risks and distributional injustice. On the other hand, the MEG is more closely aligned to the VEG, whereby, these two groups appear more comfortable with the prospect of hydrogen homes in their local communities and surrounding regions. Consolidating this analysis, similar trends are observed in respect to *trust deficit* (N = 28), whereby, the FSG proved the least trustworthy segment (*Md* = 536), followed by the BLG (*Md* = 534), the MEG (*Md* = 530), and the VEG (*Md* = 529). While group differences are less pronounced and not statistically significant (ρ = 0.770), the ordering of groups is retained, which implies a close linkage between choice and trust.

It can be inferred that a lack of trust aggravates concerns around choice-related factors, which include a potential lack of agency in decision-making and exposure to distributional injustice. These insights are revealing, as different aspects of social trust have been shown to shape energy acceptance [60,61], with trust in different stakeholder groups proving influential in shaping public perceptions of hydrogen energy systems [27,62–64]. Moreover, it is highly logical that fuel stressed respondents would stake their support for domestic hydrogen on economic impacts related to the cost-of-living crisis. On the other hand, the VEG had the highest income levels among all sub-groups [39], which appears to have diminished the significance of economic impacts. This discrepancy supports the relevance of contextual factors and financial contingencies in shaping social acceptance for hydrogen homes.

Coding procedure for comparative analysis of hydrogen acceptance factors.

Table M-5. Summary of hydrogen acceptance factors in the literature.

	SOURCE					
	This study	[27]	[65]	[66]	[66]	[67]
	METHOD OF ASSESSMENT AND SAMPLE SIZE					
	Ranked according to frequency (N = 1064)	Ranked according to importance (N = 17)	Ranked according to effect size (N = 1845)	Ranked according to frequency Full counting (N = 65)	Ranked according to frequency Binary counting (N = 65)	Ranked according to frequency N = 33
Ranking	**ACCEPTANCE FACTORS**					
1	Information (**INFO**)	Financial costs (***FIN***)	Perceived community benefits (***SOC***, ***ECON***, ***ENV***)	Information (***INFO***, ***LOG***)	Accessibility (***FIN***)	Environmental perceptions (***ENV***)
2	Image (**IMG**)	Knowledge and awareness (***INFO***)	Positive emotions (***AFF***)	Accessibility (***FIN***)	Information (***INFO***, ***LOG***)	Comprehensive perceived risks (***SOC***, ***ECON***, ***ENV***)
3	Finance (**FIN**)	Disruptive impacts (***LOG***)	Production perceptions (***ENV***)	Acceptability (***FIN***, ***F&E***)	Hydrogen markets (***ECON***)	Comprehensive perceived benefits (***SOC***, ***ECON***, ***ENV***)
4	Affect (**AFF**)	Distributional injustice (**F&E**)	Public trust (***F&E***)	Externalities (***SOC***, ***ECON***, ***ENV***)	Acceptability (***FIN***, ***F&E***)	Social trust (***F&E***)
5	Environment (**ENV**)	Consumer disengagement (***TECH***)	Negative emotions (***AFF***)	Hydrogen markets (***ECON***)	Policies and regulation (***F&E***)	Safety perceptions (***SFTY***)
6	Fairness and equity (**F&E**)	Lived experience of cooking (***TECH***)	Perceived disruptive impacts (***LOG***)	Socio-political factors (***F&E***, ***ECON***)	Socio-political factors (***F&E***, ***ECON***)	Comprehensive perceived costs (***SOC***, ***ECON***, ***ENV***)

7	Technology (**TECH**)	Safety perceptions (***SFTY***)	Perceived socio-economic costs (***SOC***, ***ECON***)	Stakeholders (***F&E***)	Stakeholders (***F&E***)	Technology perceptions (***TECH***, ***PERF***)
8	Safety (**SFTY**)	Environmental impacts (***ENV***)	Safety perceptions (***SFTY***)	Policies and regulation (***F&E***)	Externalities (***SOC***, ***ECON***, ***ENV***)	Awareness (***INFO***)
9	Economy (**ECON**)	Public trust (***F&E***)	Awareness (***INFO***)	Responsibility (***F&E***)	Socio-economic factors (***SOC***, ***ECON***)	Subjective knowledge (***INFO***)
10	Logistics (**LOG**)	Procedural injustice (***F&E***)	Knowledge (***INFO***)	Socio-economic factors (***SOC***, ***ECON***)	Research & Development (***TECH***)	Financial perceptions (***FIN***)
11	Social (**SOC**)	Technology choice (***F&E***)		Research & Development (***TECH***)	Responsibility (***F&E***)	Positive emotions (***AFF***)
12	Performance (**PERF**)	Affective response (***AFF***)		Technological safety (***SFTY***)	Technological safety (***SFTY***)	Negative emotions (***AFF***)
13		Economic impacts (***ECON***)				Objective knowledge (***INFO***)
14		Lived experience of heating (***TECH***)				

Table M-6. Recoding of hydrogen acceptance factors identified in the literature to 12 core factors.

This study (binary counting)	[27]	[65]	[66] **(full counting)**	[66] **(binary counting)**	[67]
Information (**INFO**)	Financial costs (**FIN**)	Perceived community benefits (**SOC**, **ECON**, **ENV**)	Information (**INFO**, LOG)	Accessibility (**FIN**)	Environmental perceptions (**ENV**)
Image (**IMG**)	Knowledge and awareness (**INFO**)	Positive emotions (AFF)	Accessibility (**FIN**)	Information (**INFO**, LOG)	Comprehensive perceived risks (**SOC**, **ECON**, **ENV**)
Finance (**FIN**)	Disruptive impacts (LOG)	Production perceptions (**ENV**)	Acceptability (**FIN**, **F&E**)	Hydrogen markets (**ECON**)	Comprehensive perceived benefits (SOC, **ECON**, **ENV**)
Affect (AFF)	Distributional injustice (**F&E**)	Public trust (**F&E**)	Externalities (**SOC**, **ECON**, **ENV**)	Acceptability (**FIN**, **F&E**)	Social trust (**F&E**)
Environment (**ENV**)	Consumer disengagement (**TECH**)	Negative emotions (AFF)	Hydrogen markets (**ECON**)	Policies and regulation (**F&E**)	Safety perceptions (SFTY)
Fairness and equity (**F&E**)	Lived experience of cooking (**TECH**)	Perceived disruptive impacts (LOG)	Socio-political factors (**F&E**, **ECON**)	Socio-political factors (**F&E**, **ECON**)	Comprehensive perceived costs (**SOC**, **ECON**, **ENV**)
Technology (**TECH**)	Safety perceptions (SFTY)	Perceived socio-economic costs (**SOC**, **ECON**)	Stakeholders (**F&E**)	Stakeholders (**F&E**)	Technology perceptions (**TECH**, PERF)
Safety (SFTY)	Environmental impacts (**ENV**)	Safety perceptions (SFTY)	Policies and regulation (**F&E**)	Externalities (**SOC**, **ECON**, **ENV**)	Awareness (**INFO**)
Economy (**ECON**)	Public trust (**F&E**)	Awareness (**INFO**)	Responsibility (**F&E**)	Socio-economic factors (**SOC**, **ECON**)	Subjective knowledge (**INFO**)
Logistics (LOG)	Procedural injustice (**F&E**)	Knowledge (**INFO**)	Socio-economic factors (**SOC**, **ECON**)	Research & Development (**TECH**)	Financial perceptions (**FIN**)
Social (**SOC**)	Technology choice (**F&E**)		Research & Development (**TECH**)	Responsibility (**F&E**)	Positive emotions (AFF)
Performance (PERF)	Affective response (AFF)		Technological safety (SFTY)	Technological safety (SFTY)	Negative emotions (AFF)
	Economic impacts (**ECON**)				Objective knowledge (**INFO**)
	Lived experience of heating (**TECH**)				

Table M-7. Summary of total number of hydrogen acceptance factors across studies.

This study (binary counting)	[27]	[65]	[66] (binary counting)	[67]
IMG	F&E	SOC	F&E	ENV
FIN	F&E	SOC	F&E	ENV
AFF	F&E	ECON	F&E	ENV
INFO	F&E	ECON	F&E	ENV
ENV	TECH	ENV	ECON	SOC
F&E	TECH	ENV	ECON	SOC
SFTY	TECH	INFO	ECON	SOC
TECH	FIN	INFO	ECON	ECON
ECON	INFO	AFF	FIN	ECON
LOG	LOG	AFF	FIN	ECON
SOC	SFTY	F&E	SOC	INFO
PERF	ENV	LOG	SOC	INFO
	AFF	SFTY	INFO	INFO
	ECON		LOG	AFF
			TECH	AFF
			SFTY	F&E
				SFTY
				TECH
				PERF
				FIN

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APPENDIX N. Coupling green hydrogen production to community benefits: a pathway to social acceptance? (chapter 4)

Following a draft report in September 2022 [1], the United States (US) recently followed in the footsteps of other major economies such as Japan [2], Germany [3], and France [4] in formalising its national hydrogen strategy in June 2023 [5]. Based on one energy system optimisation model proposed by Bridgeland et al. [6], low-carbon hydrogen may account for approximately 7.6% of US energy supply by 2100 and could enable more aggressive decarbonisation scenarios. Fig. N-1 illustrates the diffusion of national hydrogen strategies over the least five years.

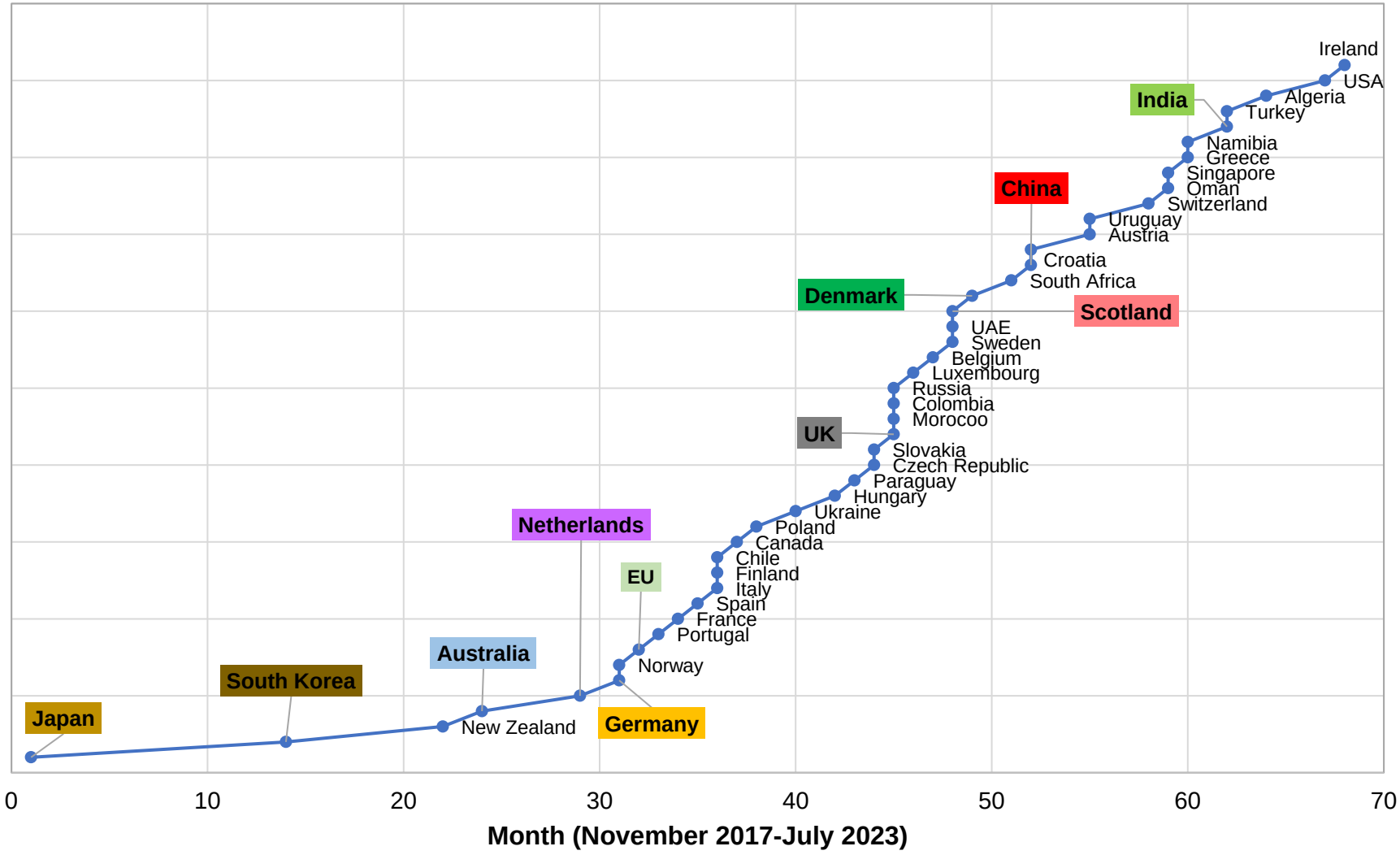


Fig. N-1. Global diffusion of National Hydrogen Strategies and Roadmaps (2017–2023).

Impacts of COVID-19 and the Russia-Ukraine war on the hydrogen economy

In 2020, Dincer [7] framed the coronavirus as a turning point in marking the shift from a ‘carbon age’ to a ‘hydrogen age’ [7], while Hosseini [8] asserts economic power “will be in the hands of the countries that establish a modern hydrogen production and utilisation system.” While Russia has resource capabilities and ambitions to supply up to 20% of the world’s hydrogen market by 2030 [9], economic sanctions and sustained wartime operations in Ukraine increasingly undermine the feasibility of this trajectory [10]. Relatedly, Overland [11] argues that the economic outlook for ‘blue’ hydrogen – dependent upon a natural gas feedstock – has worsened, while prospects for deploying ‘green’ or renewable-based hydrogen have improved.

In the face of elevated energy security risks [12], countries such as Germany, Italy and France are turning to hydrogen [13], as a critical mechanism for mitigating dependency on Russian natural gas [10,14], while a ‘dash for hydrogen gas’ is underway worldwide [15,16].In the context of the European Union’s COVID-19 recovery package, Hepburn [17] noted that “recovery policies can deliver both economic and climate goals,” recognising that investment in clean energy infrastructure should include a role for hydrogen. Notably, the European Union (EU) aims to produce 10 million tonnes of clean hydrogen by 2030, while also importing the same amount [18] to support its “long-term vision for a prosperous, modern, competitive and climate neutral Europe” [19].

Survey items and scale development

Once the survey instruments were sufficiently validated, a pre-test was conducted (N = 160), which was coordinated by a professional market research company and monitored daily by the lead researcher. During the piloting, responses were gathered from across four distinct consumer sub-groups (see Table N-3 and Fig. N-2) to verify the feasibility of the research design. Table N-1 provides full details of the survey questions pertaining to each construct and its respective indicators, as well as the scales employed, in addition to the supporting literature for deriving each item. At the end of the pilot test, minor modifications were implemented to help optimise the survey ahead of deployment by the panel company.

Table N-1. Questionnaire details and literature sources.

Construct	Indicator	Question items and framing	Scale	Supporting literature
Awareness (AWR)[a]	**AWR1**	There are a range of low-carbon energy technologies that may provide an alternative to natural gas for heating and cooking purposes. • Are you aware of these technology options?	1–5: Unaware–Extremely aware	[20–25]
	AWR2	• Are you aware that hydrogen may provide a potential low-carbon option for home heating and cooking?		
Knowledge (KNW)[b]	**KNW**	• How much do you know about hydrogen fuel?	1–5: Nothing–Significant amount	[20,22,26–30]
Public trust (ST)		How much trust do you have in the following stakeholders when it comes to supporting a cost-effective, efficient, and fair transition to hydrogen homes?		
	ST1	• Gas Distribution Network Operators	0–10: No trust–Total trust	[27–29,31–33]
	ST2	• Renewable energy producers		
	ST3	• Financial institutions		
	ST4	• The Office of Gas and Electricity Markets (Ofgem)		
	ST5	• The media		

Safety Perceptions (SP)	**SP1** **SP2** **SP3** **SP4** **SP5**	Please evaluate your current safety perceptions of hydrogen compared to natural gas for the following: • Hydrogen boilers • Hydrogen hobs • Hydrogen pipelines (i.e. transport/transmission) • Underground storage of hydrogen gas • Overall, how do you perceive the **s**afety level of hydrogen compared to natural gas in terms of production, storage, transportation, and domestic use?	0–10: Less safe–More safe	[20,21,24,27,28,34–37]
Production Perceptions (PP)	**PP1** **PP2** **PP3** **PP4** **PP5**	• What is your attitude towards the UK government supporting blue hydrogen production in the short-term (i.e. up to 2030)? • What is your attitude towards the UK government supporting blue hydrogen production over the long-term (i.e. after 2030)? • What is your attitude towards the UK government supporting green hydrogen production in the short-term (i.e. up to 2030)? • What is your attitude towards the UK government supporting green hydrogen production over the long-term (i.e. after 2030)? • How do you feel about the government's twin-track strategy**?** (i.e. with a role for blue and green hydrogen)	0–10: Opposed–Supportive	[26–28,38–40]
Perceived Disruptive Impacts (PDI)	**PDI1** **PDI2** **PDI3**	• How concerned are you about noise, traffic, and other potential inconvenience from changes to infrastructure and other hydrogen-related activities at street level? • How concerned are you about being temporarily disconnected from the gas grid for up to 3 days in summer: (i.e. during the switchover period for hydrogen homes)? • How concerned are you about disruption from engineers and technicians working within your home during the switchover period: (i.e. up to 3 days)?	1–5: Not at all concerned–Extremely concerned	[27,28,32,33,41]

Perceived Socio-economic Costs (PSC)	**PSC1** **PSC2**	To what extent do you agree or disagree with the following statements: • Switching from natural gas to hydrogen will have a negative impact on UK energy security (i.e. reliability of energy supply) • Switching from natural gas to hydrogen will lead to higher levels of fuel poverty across the UK	1–5: Strongly disagree–Strongly agree	[25,33,36,42–44]
Perceived Community Benefits (PCB)	**PCB1** **PCB2** **PCB3**	• What is your expectation for hydrogen homes delivering economic benefits such as job opportunities and income security? • What is your expectation for hydrogen homes delivering social benefits such as reduced levels of fuel poverty and improved health? • What is your expectation for hydrogen homes delivering environmental benefits such lower carbon emissions and better air quality?	0–10: Low–High expectation	[30,32,33,45–47]
Positive Emotions (PE)	**PE1** **PE2** **PE3** **PE4**	• How satisfied do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home? • How calm do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home? • How confident do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home? • How optimistic do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home?	1–5: No feeling–Very strong feeling	[22,34,48–51]
Negative Emotions (NE)	**NE1** **NE2** **NE3** **NE4**	• How discontent do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home? • How worried do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home? • How fearful do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home? • How pessimistic do you feel about the prospect of using a hydrogen boiler and hydrogen hob within your home?	1–5: No feeling–Very strong feeling	[22,34,48–51]
		Please evaluate your current level of support or opposition for the following:		

Domestic Hydrogen Acceptance (ACPT)	**ACPT1** **ACPT2** **ACPT3**	• Domestic hydrogen becoming a critical part of the UK's energy future • Hydrogen replacing natural gas in your local area before 2030 • Switching your home to both hydrogen heating and hydrogen cooking before 2030	0–10: Opposed–Supportive	[42,52–54]
Willingness to Adopt Domestic Hydrogen (WTA)	**WTA1** **WTA2** **WTA3**	• What is your level of willingness to switch to a hydrogen boiler before 2030? • What is your level of willingness to switch to a hydrogen hob before 2030? • What is your level of willingness to switch to a hydrogen home before 2030? (i.e. both hydrogen heating and cooking)	1–5: Not willing at all–Extremely willing	[42,52–54]

[a] For the Awareness scale, the following options were given:

- No, I was unaware before today
- Yes, I'm slightly aware
- Yes, I'm somewhat aware
- Yes, I'm very aware
- Yes, I'm extremely aware

[b] For the Knowledge scale, the following options were given:

- I know nothing about hydrogen fuel but may have heard something about it in the past
- I know a little about hydrogen fuel and understand some basic details
- I know a moderate amount about hydrogen fuel and can explain some basic information about it
- I know a lot about hydrogen fuel and feel confident explaining information about it
- I know a significant amount about hydrogen fuel and feel very confident explaining information about it

Modelling public trust within the DHAM

While public trust can be modelled as a mediator variable [31,55], this study focuses exclusively on direct effects. This approach reflects the notion that public trust is especially influential during the early stages of technology diffusion, wherein consumers may be more inclined to make judgements vis-à-vis the assessments of technical experts [56], thereby reducing the burden of cognitive complexity in decision-making [57]. Such an inclination typically stems from a knowledge deficit, which links to the notion that public trust and reliance on others for information are deeply intertwined [49]. This relationship is reinforced when decisions are highly technical and time-intensive [58], which may lead to affect-based judgements over cognitive decision-making [49,59]; otherwise distinguished in terms of the analytic and experiential systems [60]. It follows that reducing the burden of cognitive complexity associated with the wider hydrogen transition may steer the potential for converting a proportion of existing gas users (i.e. ~84% of the UK housing stock) [61] to hydrogen homes.

Research design and sample composition

In addition to establishing a comprehensive survey design to account for multiple acceptance constructs, a series of measures were implemented to approximate a broadly nationally representative sample where relevant and plausible. Additionally, by incorporating a Fuel Stressed Group (FSG) (see Table N-3 and Fig. N-2), the sample accounts for the increasing prevalence of fuel poverty pressures in the UK [62,63]. Similarly, the inclusion of participants with different levels of technology knowledge and interest, and environmental engagement assists in covering a spectrum of consumer profiles within the final sample.

Specifically, quotas were applied for the following socio-demographic variables: age, gender, housing tenure, housing type and location. Additionally, all survey respondents were existing users of gas boilers and hobs, with at least moderate involvement in decision-making around the purchase of their heating and cooking appliances. Furthermore, all participants attributed at least moderate importance to the ability to choose these appliances. Both questions were measured using a five-point Likert scale where the moderate response represented the mid-point, reflecting the intention to recruit respondents more likely to actively engaged with a prospective transition to hydrogen homes, or other low-carbon domestic energy technologies.

Regarding the age quota, the sample was slightly over-represented for the youngest age group (18–34), moderately over-represented for the middle age group (35–54) and significantly under-represented for the oldest age group (55+). This result may partially reflect the difficulty of securing online survey responses from older internet users, but could also infer that this demographic is somewhat less engaged with hydrogen. For example, a recent government survey reported the youngest demographic group (16–24) is 1.4 times more likely to say they know at least a fair amount about hydrogen (21%) compared to older demographics (15%) [64].

In terms of gender, the sample was slightly over-represented by female respondents, while participants were close to equally recruited from different regions of the UK (see Table N-2). Additionally, filters were applied to target citizens owning a property outright or with a mortgage, as this demographic group is more likely to be directly impacted by a switch to domestic hydrogen [65]. Finally, semi-detached and detached property owners were over-represented compared to owners of flats, apartments, or

bungalows, and to a lesser degree, terrace houses. While this discrepancy appears sub-optimal at face value, domestic hydrogen is likely less suitable for property blocks and smaller units where electric heating and induction hobs are increasingly prevalent [66]. Overall, a broadly national representative survey sample was secured (N = 1845), albeit with room for improvement around variables such as age and housing tenure in subsequent studies.

Table N-2. Sample characteristics and comparison to UK population.

Socio-demographic variable	Sample (%)	UK population (%)	Difference (%)
Age			
18-34	35.5	32.6	+2.9
35-54	39.2	30.6	+8.6
55+	25.3	36.8	-11.5
Gender			
Male	43.9	48.8	-4.9
Female	56.1	51.2	+4.9
Housing tenure			
Property owned outright	37.2	57.1	-19.9
Property owned with mortgage	62.8	42.9	+19.9
Housing type			
Flat, apartment or bungalow	12.3	29.6	-17.3
Detached house	29.1	17.9	+11.2
Semi-detached house	38.5	24.9	+13.6
Terrace house	20.2	27.6	-7.4
Total number of occupants per property			
1	10.0	n/a[a]	
2	30.2	n/a	
3+	59.8	n/a	
Highest education level			
GCSE/O-Level or lower	21.7	n/a	
Vocational/NVQ	24.2	n/a	
Postgraduate qualification	21.4	n/a	
Degree or equivalent	32.7	n/a	
Annual income bracket (before tax)			
Less than £23,500	26.6	n/a	
More than £23,500 but less than £31,500	20.8	n/a	
More than £31,500 but less than £41,500	18.9	n/a	
More than £41,500 but less than £62,500	21.7	n/a	
More than £62,500	12.1	n/a	
Location			
South West and Wales	12.5	13.4	-0.9
Midlands and East of England	25.7	26.2	-0.5

South east and London	27.5	27.2	+0.3
North of England and Scotland	34.2	33.0	+1.2
Area type			
Inner City or industrial	8.9	n/a	
Suburban	52.1	n/a	
Urban	21.6	n/a	
Rural	17.4	n/a	

Source: Authors' compilation based on [67–69].
[a] n/a denotes the decision to exclude these variables when setting quotas, therefore population data is not reported here.

Consumer sub-groups

The sample is composed of respondents from four specific consumer segments: a Very technology and environmentally engaged Group (VEG); a Moderately technology and environmentally engaged Group (MEG); a Fuel Stressed Group (FSG) who are non-engaged in technology and the environment; and a Baseline Group (BLG) who are non-engaged in technology and the environment, and like the VEG and MEG are also not fuel stressed. Nevertheless, certain consumer segments proved harder to reach than others (Table N-3), which led to a degree of over- and under-representation among the targeted sub-groups.

The research design aligns to the notion that different parts of society will contribute towards shaping the acceptability of the hydrogen economy, which like other low-carbon energy transitions [70,71] rests on engagement with potential early adopters [72,73] and environmentally engaged consumers [74,75], as well as citizens facing fuel poverty or high levels of fuel stress [62,76,77]. Consequently, the dataset supports opportunities for carrying out multigroup analysis (MGA), which is a focal point of follow-up research [78]

Table N-3 describes the breakdown of each consumer sub-group composing the survey sample (N =1845). The ideal target was to secure an equally balanced representation among three of sub-groups (i.e. MEG, VEG, FSG), alongside a larger Baseline Group (BLG) of ~40%. Higher occurrences of incomplete answers and straight-lining responses resulted in a final sample of 677 for the BLG (~36.7%). During the data collection, the Very Engaged Group (VEG) proved harder to reach, leading to partial under-representation (N = 331, 17.9%). By comparison, the Moderately Engaged Group (MEG) was easier to secure and somewhat over-represented

(24.8%). Finally, the Fuel Stress Group (FSG) was in line with the original quotas (20.5%).

Table N-3. Consumer sub-groups composing the survey sample.

Sub-group	Consumer specifications
Moderately Engaged Group (MEG) N = 458	• Moderate level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Moderate interest and engagement in environmental issues • Not experiencing fuel stress
Very Engaged Group (VEG) N =331	• High level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Strong interest and engagement in environmental issues • Not experiencing fuel stress
Fuel Stress Group (FSG) N = 379	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Living in fuel poverty or experiencing high levels of fuel stress
Baseline Group (BLG) N = 677	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Not experiencing fuel stress

Fig. N-2 describes the composition of the sample according to the following filters: technology and environmental engagement level, and fuel poverty status which is denoted by whether respondents were experiencing fuel stress. The broader and more familiar term ‘fuel poverty’ is used to capture these dynamics in the figure below.

One survey was deployed to recruit participants for the MEG and VEG and then separated the groups according to a specific cut-off: ≥12 points out of the theoretical maximum of 15 points corresponded to the VEG; ≥9 but <12 corresponded to the MEG; and <9 corresponded to the BLG and FSG. Three questions measured on a five-point Likert scale were used: two questions measured technology engagement level (knowledge of renewable energy technologies, and willingness to be an early

adopter of new energy technologies), while one question measured knowledge and awareness of environmental issues such as climate change.

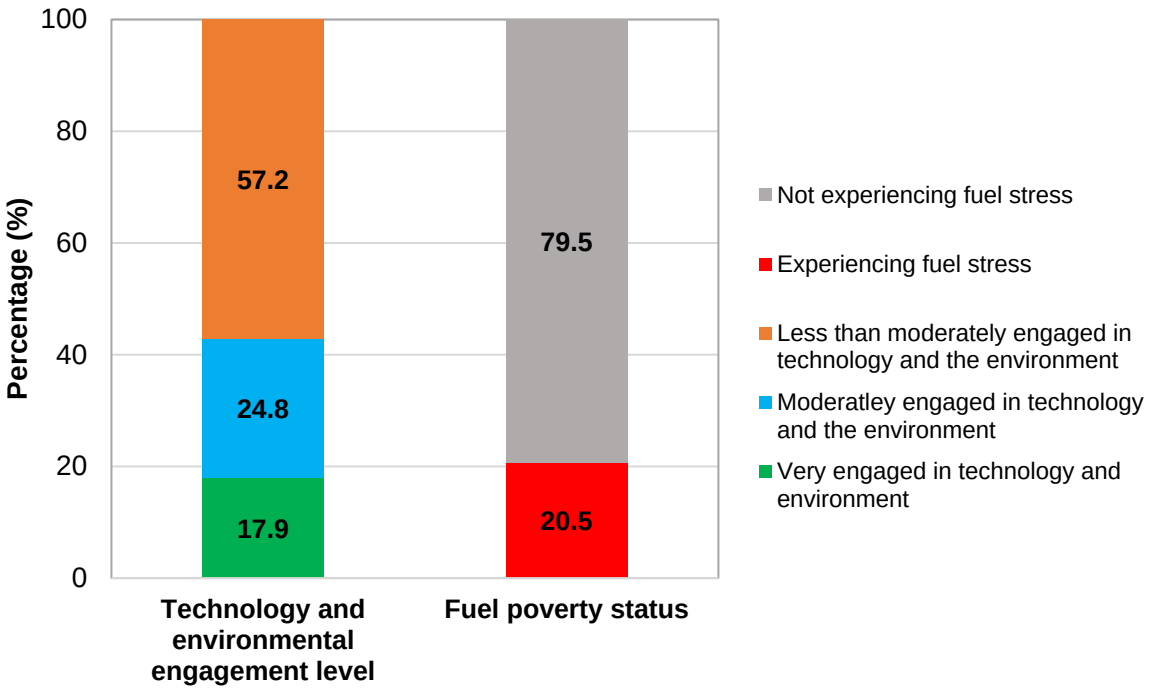


Fig. N-2. Composition of consumer sub-groups by categorical filters.

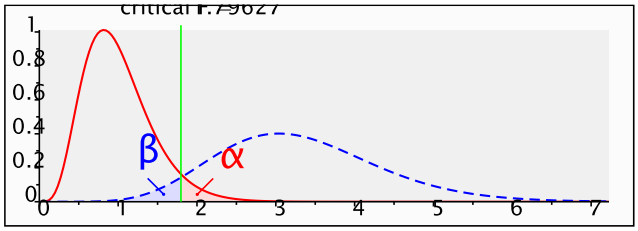
In total, three surveys were deployed as reported in Table N-4, which provides the incidence and responses rates for each of the Qualtrics surveys, which ran from October 6th to December 23rd, 2023.

Table N-4. Response rate across sub-samples.

Consumer sub-groups	Number of respondents accessed	Number of completed surveys	Final sample size after data cleaning	Incidence rate after data cleaning	Final incidence rate
BLG	12098	789	677	85.8%	5.6%
MEG and VEG	7950	902 (509; 393)	789 (458; 331)	87.5% (90.0%; 84.2%)	9.9% (5.8%; 4.2%)
FSG	5112	409	379	92.7%	7.4%
Total	25160	2100	1845	87.8%	7.3%

Statistical test for validating sample size specifications

While PLS-SEM is well equipped to handle both small and large sample sizes [79], researchers should carry out tests to specify the ability to detect effect sizes [80,81]. Foremost, researchers should complement recent recommendations such as the inverse square root and gamma-exponential methods [82] with model-specific estimates to determine sample size requirements. Fig. N-3 provides results on sample size requirements for testing effect sizes. We used G*Power software to verify the parameters. Since our sample was relatively large (*N* = 1845), it was suitable for PLS-SEM, however, we checked the results from G*Power to clarify the reliability of (small) effect sizes.



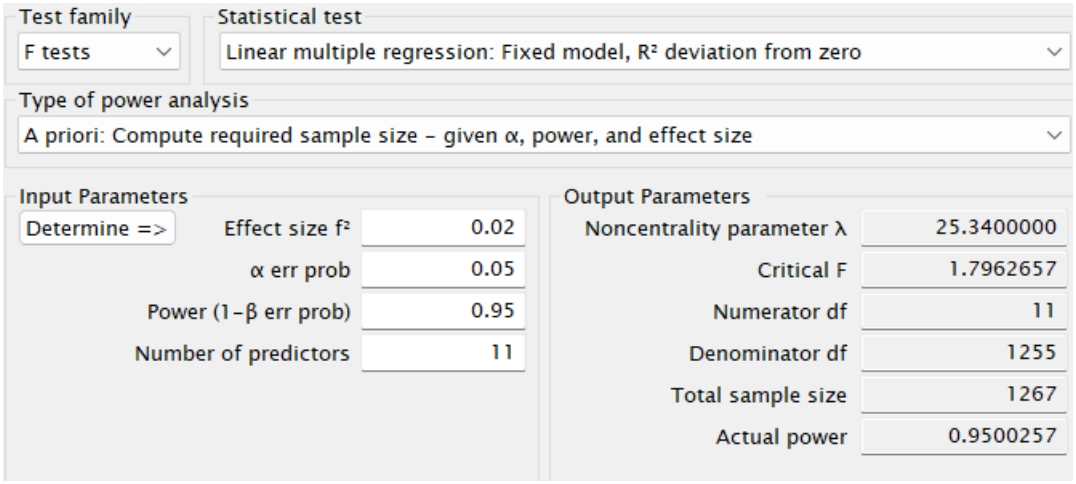


Fig. N-3. Power test to determine the minimum sample size for an effect size of 0.02 at 95% significance.

Assessment of the common method bias

Common method bias (CMB) may arise when the measurement method deployed in the survey (i.e. question structure and instructions etc.) or other factors (e.g. social desirability response) causes the indicators to share a certain amount of common variation [86], which can lead to biased results [87]. Harman's single factor test may help detect instances of CMB, however, the method is not without its limitations [88]. The procedure requires that the overall variance extracted falls below the threshold of 50%. This sample demonstrated an overall variance of 29.5% (see Table N-5). An alternative to assessing collinearity has been proposed by Kock and Lynn [89] which involves generating a random variable to serve as the (sole) endogenous construct in the model. This procedure was also applied, with all variance inflation factor (VIF) scores for the structural model falling below the recommended threshold of 3.3 [86].

Table N-5. Harman single factor test for common method bias.

Total Variance Explained					
Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**	
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**
1	11.551	28.877	28.877	10.935	**27.338**
2	4.236	10.591	39.468		
3	2.827	7.068	46.536		
4	2.194	5.486	52.022		
5	1.932	4.83	56.852		
6	1.628	4.071	60.923		
7	1.304	3.261	64.184		
8	1.18	2.949	67.133		
9	1.082	2.705	69.838		
10	0.929	2.322	72.161		
11	0.824	2.059	74.22		
12	0.658	1.646	75.866		
13	0.635	1.588	77.454		
14	0.58	1.45	78.904		
15	0.531	1.328	80.232		
16	0.493	1.233	81.465		
17	0.476	1.191	82.655		
18	0.453	1.132	83.787		
19	0.433	1.082	84.868		
20	0.425	1.064	85.932		
21	0.407	1.016	86.948		
22	0.383	0.958	87.906		
23	0.371	0.926	88.833		

24	0.349	0.871	89.704		
25	0.338	0.846	90.55		
26	0.337	0.843	91.393		
27	0.331	0.827	92.22		
28	0.328	0.82	93.04		
29	0.307	0.767	93.807		
30	0.297	0.742	94.549		
31	0.291	0.729	95.278		
32	0.278	0.694	95.972		
33	0.269	0.672	96.644		
34	0.239	0.596	97.24		
35	0.228	0.57	97.81		
36	0.218	0.546	98.355		
37	0.187	0.467	98.822		
38	0.171	0.428	99.25		
39	0.167	0.419	99.669		
40	0.133	0.331	100		

Assessment of skewness and kurtosis

At the initial stage of data analysis, skewness and kurtosis should be assessed to determine the symmetry and distribution of the sample [81,83]. For both measurements, values between +1 and -1 are considered excellent (i.e. normally distributed), while values between +2 and -2 are deemed acceptable [84]. Beyond this boundary, values are indicative of substantial non-normality [81], although some researchers posit more liberal ranges [85]. Skewness and kurtosis tests were conducted using statistical analysis [83], which confirmed all values where within the preferred threshold of +/-1 (see Table N-6).

Table N-6. Assessment of indicator means, standard deviation, reliability, and validity.

Indicator	Mean	SD	Skewness	Kurtosis	VIF score
AWR1	2.051	0.969	0.095	0.742	1.780
AWR2	1.953	1.075	-0.015	0.910	1.780
PCB1	6.276	2.019	-0.423	0.105	1.888
PCB2	6.230	2.134	-0.462	0.046	1.970
PCB3	7.021	2.074	-0.577	0.060	1.568
PDI1	2.364	0.937	0.450	0.021	1.315
PDI2	2.642	1.109	0.401	-0.506	1.795
PDI3	2.608	1.073	0.376	-0.403	1.835
KNW	1.957	0.962	0.926	0.487	1.000
NE1	2.399	1.067	0.232	-0.683	1.701
NE2	2.546	1.062	0.204	-0.610	2.725
NE3	2.395	1.102	0.408	-0.594	2.892
NE4	2.423	1.085	0.348	-0.599	1.929
PSC1	2.766	1.000	0.285	-0.423	1.494
PSC2	2.977	0.984	0.091	-0.471	1.494
PE1	3.046	0.986	-0.255	-0.050	2.379
PE2	3.010	0.977	-0.178	-0.093	2.081
PE3	3.007	0.982	-0.117	-0.194	2.296
PE4	3.145	1.001	-0.271	-0.219	2.210
PP1	5.571	2.001	-0.116	-0.190	1.650
PP2	6.776	2.035	-0.269	-0.442	2.292
PP3	7.275	2.059	-0.464	-0.408	2.257
PP4	6.441	1.740	-0.141	0.007	1.807
PP5	5.682	1.816	-0.049	0.010	2.219
SP1	5.929	2.007	-0.148	-0.231	*3.229*
SP2	5.924	2.041	-0.202	-0.228	*3.026*
SP3	5.801	2.033	-0.157	-0.262	2.705
SP4	5.679	2.142	-0.152	-0.347	2.381
SP5	5.963	1.94	-0.255	-0.128	2.826
ST1	5.234	2.377	-0.321	-0.520	2.411
ST2	5.816	2.383	-0.469	-0.381	1.916
ST3	4.949	2.371	-0.207	-0.548	2.138

ST4	5.472	2.449	-0.398	-0.473	1.890
ST5	4.034	2.459	0.158	-0.824	1.670
ACPT1	6.430	2.103	-0.483	0.007	*3.016*
ACPT2	6.344	2.234	-0.510	-0.029	**3.899**
ACPT3	6.382	2.279	-0.543	-0.022	**3.642**
WTA1	2.943	1.003	0.085	-0.359	**4.053**
WTA2	2.899	1.014	0.179	-0.419	**4.370**
WTA3	2.870	1.039	0.207	-0.467	**3.533**

Bold italics denote VIF scores above 3.3, while *italics* denotes VIF scores above 3.0 but below 3.3. A more liberal cut-off of 5.0 is also suggested in the literature to assess potential multicollinearity issues. While VIF values are not formally required to assess reflective constructs, the results provide further confirmation of the validity of our measurement instruments.

Comparative analysis to BEIS Public Attitudes Tracker

Data collected by the Department for Business, Energy & Industrial Strategy (BEIS), as part of the Public Attitudes Tracker (PAT) [64], is incorporated into the analysis to help validate findings on perceived socio-economic costs (PSC) and perceived community benefits (PCB). BEIS collected two measures related to the perceived costs of energy, namely, consumer attitudes towards "power cuts becoming more frequent in the future" and "steep rises in energy prices in the future" [64]. The values were measured on a four-point Likert scale: not at all concerned, not very concerned, fairly concerned, and very concerned. We removed the 'don't know' category (3% and 2%).

These survey items can be linked to PSC1 (energy security impacts) and PSC2 (fuel poverty impacts), respectively. The first measure indicates that 33% and 43% of the public (N = 4462) are fairly concerned and very concerned about prospective power cuts (*M* = 3.22), whereas 72% (N = 4487) are very concerned about price hikes (*M* = 3.67) [64].

Since perceived socio-economic costs was measured on a five-point Likert scale, the BEIS (four-point) scale has been adjusted to provide the following comparison: PSC1 = 2.77, BEIS1 = 4.03; PSC2 = 2.98, BEIS2 = 4.59. While the results are in general alignment to BEIS, agreement and disagreement levels linked to statements on PSC1 and PSC2 were investigated, as opposed to measuring levels of concern, which may further explain why perceived socio-economic costs were moderate as opposed to high. At the same time, it is plausible that consumers do not consider the hydrogen transition to be front and centre of future (socio-)economic concerns.

A similar approach is followed to contextualise the findings on perceived community benefits. Drawing on the BEIS PAT dataset [64], consumer acceptance (i.e. self-rated 'happiness') in relation to renewable energy projects (onshore wind farms and solar panel farms) stems primarily from the perception of environmental benefits whereas socio-economic benefits are of secondary importance in line with Fig. 4-6.

Furthermore, 89% of respondents (*N* = 1859) cite environmental benefits (i.e. combatting climate change and reducing carbon emissions) as the reason for supporting CCS, while economic benefits and job creation emerge as secondary explanations (34% and 35%) [64]. While the divergence between environmental

(PCB3) and socio-economic benefits (i.e. PCB1 and PCB2) is less pronounced in the domestic hydrogen study, similar patterns are observed in terms of prioritisation, as reported in Table N-7.

Table N-7. Calculations for perceived benefits of domestic hydrogen from BEIS PAT dataset.

		Renewable energy technology (RET)			
Benefit type	**Statement provided in survey**	**Onshore wind farm**	**Solar panel farm**	**Mean value (RET)**	**Mean value (benefit)**
• Economic benefit	• It would lead to lower dependence on foreign energy sources	56.0	57.0	56.5	**39.3**
• Economic benefit	• I believe renewable energy is cheaper to producer than energy from fossil fuels	34.0	39.0	36.5	
• Economic benefit	• I think it would create jobs	34.0	30.0	32.0	
• Economic benefit	• I think it would benefit the local economy	31.0	34.0	32.5	
• Social benefit	• I think it would benefit the local community	n/a	34.0	0.34	**34.0**
• Environmental benefit	• It would provide a sustainable source of power	79.0	82.0	80.5	**61.3**
• Environmental benefit	• I think it's important for reducing emissions	75.0	76.0	75.5	
• Environmental benefit	• I think it would improve air quality	26.0	30.0	28.0	

Measurement model assessment

Dillon-Goldstein rho_c (ρ_C) can be considered at the upper bound for internal consistency reliability, while Henseler and Dijkstra rho_a (ρ_A) usually lies between CA and ρ_C, thereby serving as a more robust measure of internal consistency [90]. ρ_A fell

between the recommended values of 0.70 and 0.90 for all exogenous constructs, except safety perceptions ($\rho_A = 0.92$) and negative emotions ($\rho_A = 0.90$). Additionally, the endogenous construct (SA) measured marginally higher than the recommended upper bound ($\rho_A = 0.92$). However, content validity was retained since ρ_A fell below 0.95 in all cases, thereby minimising the risk of indicator redundancy [90]. Table N-8 reports cross-loadings, which supports results described in Section 4.6.2.2 of the main manuscript.

Table N-8. Cross loadings.

	AWR	ACPT	KNW	NE	PCB	PDI	PSC	PE	PP	PT	SP	WTA
ACPT1	0.158	**0.916**	0.139	-0.318	0.638	-0.265	-0.356	0.487	0.599	0.515	0.423	0.531
ACTP2	0.136	**0.940**	0.119	-0.358	0.632	-0.294	-0.348	0.516	0.561	0.489	0.456	0.593
ACTP3	0.168	**0.934**	0.168	-0.304	0.619	-0.274	-0.302	0.537	0.516	0.517	0.451	0.625
AWR1	**0.934**	0.168	0.442	0.054	0.098	0.046	0.040	0.240	0.205	0.179	0.065	0.230
AWR2	**0.886**	0.129	0.431	0.068	0.063	0.005	0.063	0.210	0.171	0.173	0.073	0.208
PCB1	0.087	0.529	0.078	-0.122	**0.844**	-0.100	-0.218	0.376	0.415	0.393	0.474	0.359
PCB2	0.076	0.548	0.069	-0.156	**0.861**	-0.095	-0.266	0.375	0.398	0.400	0.522	0.381
PCB3	0.070	0.636	0.050	-0.298	**0.843**	-0.209	-0.369	0.391	0.538	0.362	0.411	0.398
PDI1	0.089	-0.167	0.150	0.348	-0.095	**0.687**	0.263	-0.044	-0.096	-0.023	0.008	-0.082
PDI2	0.012	-0.256	0.033	0.334	-0.132	**0.866**	0.208	-0.119	-0.127	-0.114	-0.029	-0.174
PDI3	0.002	-0.291	0.019	0.351	-0.166	**0.893**	0.249	-0.145	-0.150	-0.136	-0.035	-0.197
KNW	0.479	0.153	**1.000**	0.102	0.076	0.065	0.138	0.277	0.216	0.225	0.129	0.287
NE1	0.044	-0.169	0.102	**0.738**	-0.094	0.284	0.295	0.052	-0.135	0.008	-0.015	-0.062
NE2	0.051	-0.337	0.054	**0.894**	-0.208	0.395	0.377	-0.119	-0.183	-0.080	-0.147	-0.246
NE3	0.060	-0.315	0.085	**0.899**	-0.206	0.358	0.379	-0.086	-0.185	-0.063	-0.136	-0.218
NE4	0.066	-0.319	0.117	**0.842**	-0.242	0.343	0.381	-0.087	-0.204	-0.088	-0.079	-0.207
PE1	0.196	0.476	0.243	-0.047	0.393	-0.103	-0.182	**0.870**	0.303	0.328	0.306	0.523
PE2	0.187	0.435	0.239	-0.079	0.329	-0.114	-0.138	**0.836**	0.281	0.303	0.299	0.489
PE3	0.248	0.457	0.270	-0.068	0.363	-0.117	-0.141	**0.860**	0.279	0.336	0.308	0.547
PE4	0.220	0.522	0.206	-0.107	0.447	-0.126	-0.227	**0.867**	0.345	0.345	0.331	0.541
PP1	0.077	0.266	0.143	0.019	0.256	0.036	-0.015	0.159	**0.550**	0.278	0.271	0.155
PP2	0.174	0.490	0.144	-0.217	0.450	-0.165	-0.282	0.290	**0.814**	0.275	0.233	0.324
PP3	0.150	0.522	0.094	-0.265	0.486	-0.195	-0.312	0.292	**0.814**	0.284	0.259	0.309
PP4	0.209	0.535	0.234	-0.160	0.450	-0.124	-0.230	0.326	**0.818**	0.396	0.316	0.350
PP5	0.153	0.400	0.220	-0.098	0.344	-0.064	-0.131	0.238	**0.769**	0.322	0.279	0.249
PSC1	0.054	-0.336	0.130	0.389	-0.287	0.257	**0.900**	-0.180	-0.283	-0.057	-0.103	-0.209
PSC2	0.042	-0.302	0.114	0.368	-0.321	0.248	**0.874**	-0.180	-0.210	-0.052	-0.129	-0.212
PT1	0.153	0.443	0.183	-0.081	0.352	-0.093	-0.040	0.299	0.334	**0.860**	0.353	0.261
PT2	0.178	0.566	0.190	-0.175	0.479	-0.179	-0.159	0.385	0.426	**0.831**	0.374	0.363
PT3	0.168	0.383	0.200	0.019	0.326	-0.051	0.026	0.308	0.271	**0.813**	0.387	0.233
PT4	0.103	0.429	0.108	-0.057	0.374	-0.089	-0.075	0.268	0.317	**0.803**	0.329	0.204
PT5	0.180	0.289	0.254	0.083	0.210	-0.028	0.090	0.244	0.227	**0.698**	0.305	0.196
SP1	0.065	0.429	0.093	-0.122	0.511	-0.032	-0.136	0.309	0.322	0.380	**0.886**	0.297
SP2	0.065	0.415	0.096	-0.138	0.489	-0.025	-0.115	0.302	0.297	0.356	**0.873**	0.289
SP3	0.049	0.402	0.109	-0.094	0.464	-0.028	-0.131	0.306	0.294	0.373	**0.864**	0.291

SP4	0.064	0.385	0.127	-0.089	0.435	-0.031	-0.086	0.317	0.296	0.379	**0.835**	0.283
SP5	0.081	0.436	0.138	-0.088	0.480	-0.004	-0.095	0.341	0.314	0.407	**0.881**	0.320
WTA1	0.243	0.589	0.286	-0.194	0.420	-0.178	-0.203	0.580	0.355	0.301	0.311	**0.940**
WTA2	0.230	0.579	0.268	-0.228	0.422	-0.189	-0.229	0.576	0.344	0.290	0.325	**0.945**
WTA3	0.207	0.601	0.256	-0.235	0.421	-0.179	-0.235	0.570	0.366	0.323	0.326	**0.933**

Results for establishing discriminant validity

Traditionally, the Fornell Larcker criterion [91] has been used to assess discriminant validity, wherein each construct's AVE is compared to the squared inter-construct correlation of its own construct and all other (reflectively) measured constructs [90]. Indicators should load more strongly on their intended constructs than on other constructs to support discriminant validity [88], as illustrated Table N-9.

Following the critique of Henseler et al. [92], the heterotrait-monotrait (HTMT) ratio of correlations has been widely adopted as a more robust measure of discriminant validity [93], given its additional levels of sensitivity and specificity [94]. Discriminant validity is established when values fall below 0.85 for each construct, or below 0.90 when constructs share conceptually similarity [92]. HTMT values fell below the more conservative value of 0.85, thereby establishing discriminant validity for each construct.

Table N-9. Fornell Larcker results for assessment of discriminant validity.

	AWR	**PCB**	**PDI**	**KNW**	**NE**	**PSC**	**PE**	**PP**	**SP**	**SA**	**ST**
AWR	0.910										
PCB	0.091	0.849									
PDI	0.031	-0.164	0.821								
KNW	0.479	0.076	0.065	1.000							
NE	0.066	-0.233	0.412	0.102	0.846						
PSC	0.054	-0.341	0.284	0.138	0.427	0.887					
PE	0.248	0.449	-0.134	0.277	-0.088	-0.203	0.859				
PP	0.208	0.536	-0.154	0.216	-0.212	-0.280	0.353	0.760			
SP	0.075	0.549	-0.027	0.129	-0.123	-0.130	0.363	0.351	0.868		
SA	0.166	0.677	-0.299	0.152	-0.351	-0.360	0.552	0.601	0.477	0.930	
ST	0.193	0.452	-0.122	0.225	-0.075	-0.061	0.383	0.407	0.436	0.545	0.803

Structural model assessment

Fig. N-4 visualises the structural model with t-statistics provided at the indicator level, instead of loadings. Additionally, t-statistic are provided in brackets to help illustrate the significance of path coefficients more clearly.

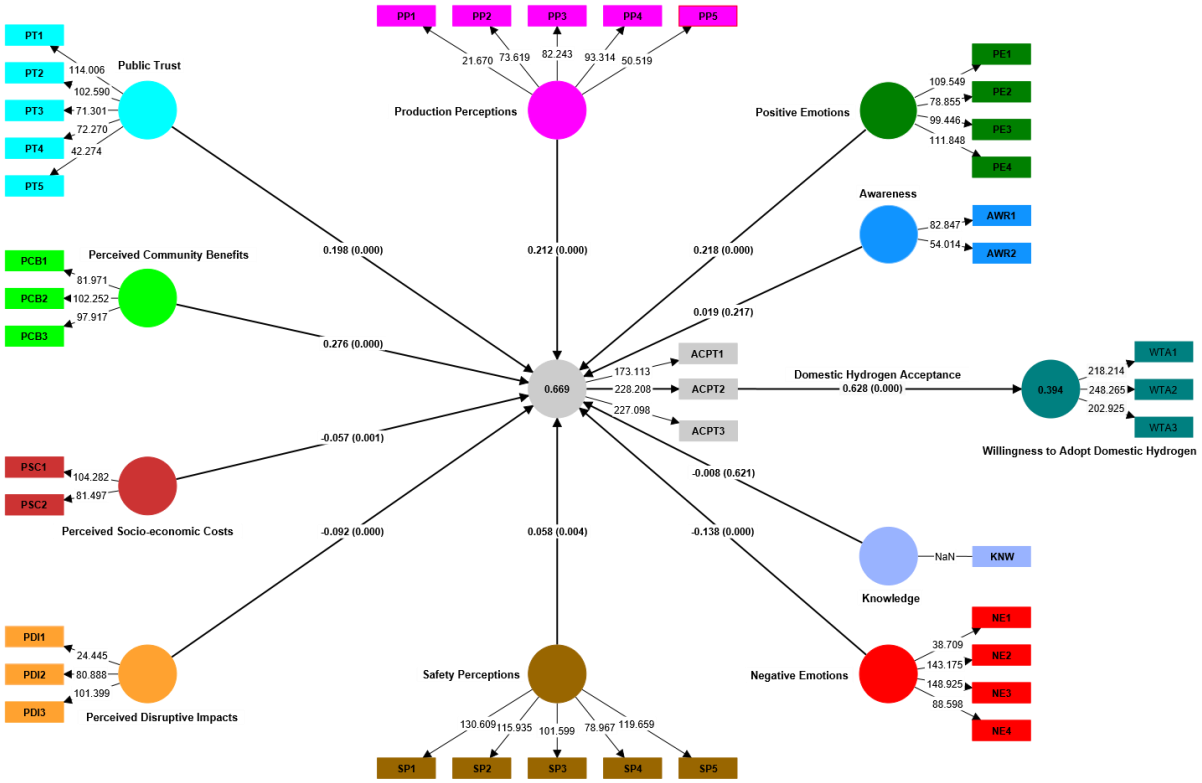


Fig. N-4. Structural model results with t-statistics at the indicator level.

Importance-performance map analysis

IMPA helps visualise the relationships between antecedent constructs and the target construct [95–97] by integrating the dimension of performance to the analysis (i.e. latent variable index value), alongside importance (i.e. total effects on the target construct) [96]. Specifically, a one unit-point increase in the performance of a given antecedent construct (Y_1) increases the performance of the target construct by the corresponding total effect of Y_1 [95]. Thus, constructs positioned at the lower right quadrant of the matrix (i.e. where importance is high, but performance is low) or in nearest proximity, imply greater scope for potential improvement in the target construct [95,96].

Sustainability scholars have adopted the IMPA as an innovative tool [98] to support optimal resource allocation strategy [97]. Among recent examples, Hossain et al. [99] applied the IMPA to examine the consumer attitudes towards energy-efficient household appliances in Bangladesh (N = 1510), while Bamidele et al. [98] explored the impact of various constructs on the perceived green performance of Nigeria's

aviation industry (N = 220). Furthermore, Agarwal et al. [97] extended their analysis on the factors influencing the rooftop solar adoption in India's Agra region (N = 225) by drawing on IMPA. Moreover, internalising results from an IMPA is especially critical during times of economic instability [100] such as the current energy crisis [62,97, 101].

Table N-10 reports the results for the importance-performance map analysis conducted at the construct level, while Fig. N-5 provides the visual output from PLS-SEM. Additionally, Fig. N-6 illustrates the results with the negative scale removed, which further demonstrates areas of strategic interest and value, while Table N-11 reports all values for the IMPA at the indicator level.

Table N-10. Total effects and latent variable index values for exogenous constructs.

Construct	Importance (total effects)	Performance (LV index values)
Awareness	0.019	25.277
Knowledge	-0.008	23.930
Public trust	0.198	52.260
Production Perceptions	0.214	63.823
Safety Perceptions	0.058	58.664
Disruptive Impacts	0.092	38.893
Perceived Costs	0.058	46.667
Community Benefits	0.276	65.389
Positive Emotions	0.217	51.382
Negative Emotions	0.138	36.224

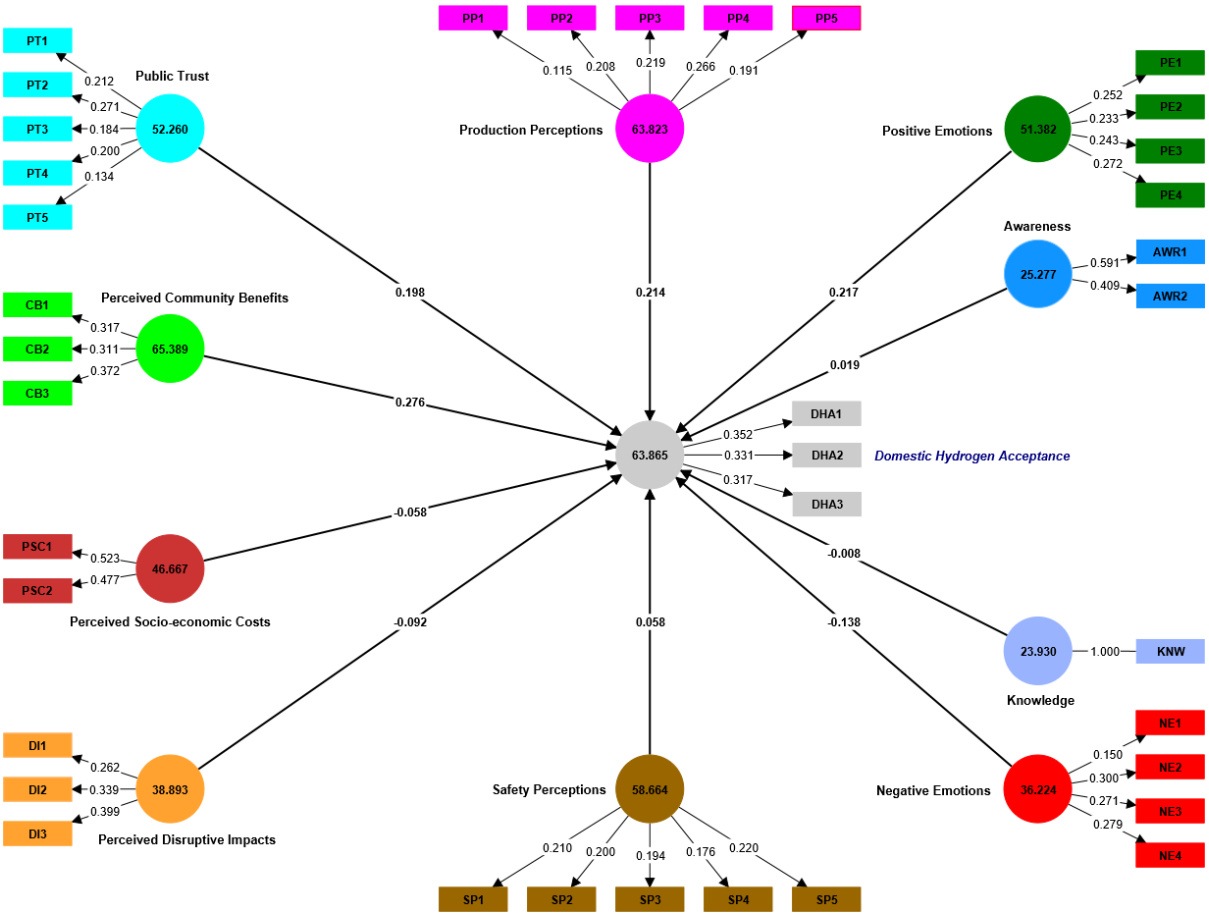


Fig. N-5. Modelling results for Importance-performance map analysis.

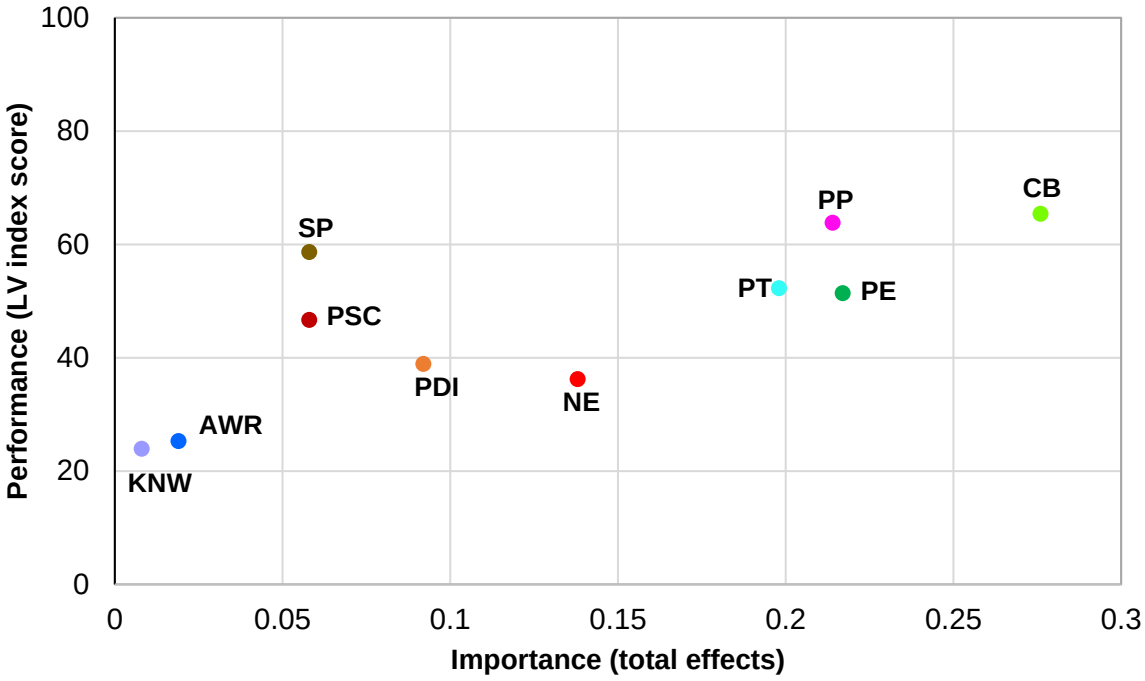


Fig. N-6. Importance Performance Map Analysis for constructs rescaled to positive axis for importance.

Blue = Awareness (AWR); Lilac = Knowledge (KNW); Turquoise = Public trust (PT); Purple = Production Perceptions (PP); Brown = Safety Perceptions (SP); Orange = Disruptive Impacts (DI); Dark red = Perceived Costs (PC); Bright green = Community Benefits (CB); Green = Positive Emotions (PE); Red = Negative Emotions (NE)

Table N-11. Total effects and latent variable index values for exogenous constructs for indicators.

Indicator	Importance (total effects)	Performance (LV index values
AWR1	0.012	26.274
AWR2	0.009	23.835
KNW	-0.008	23.930
PT1	0.052	52.336
PT2	0.066	58.157
PT3	0.044	49.491
PT4	0.050	54.715
PT5	0.034	40.336
PP1	0.033	55.713
PP2	0.061	67.756
PP3	0.065	69.726
PP4	0.067	64.407
PP5	0.050	56.818
SP1	0.014	59.290
SP2	0.013	59.241
SP3	0.013	58.005
SP4	0.012	56.786
SP5	0.014	59.626
PDI1	-0.026	34.106
PDI2	-0.040	41.057
PDI3	-0.045	40.190
PSC1	-0.034	44.160
PSC2	-0.031	49.417
PCB1	0.100	62.764
PCB2	0.104	62.298
PCB3	0.121	70.211
PE1	0.063	51.152
PE2	0.058	50.257
PE3	0.061	50.176
PE4	0.070	53.631
NE1	-0.024	34.973
NE2	-0.048	38.659
NE3	-0.044	34.878
NE4	-0.045	35.583

Illustrative example of reflective-formative construct for perceived community benefits

Fig. N-7 Illustrates how a reflective-formative construct can be effectively formed in follow-up studies, taking perceived community benefits (PCB) as an example. In a reflective-formative construct, the lower-order constructs (economic benefits, social benefits, environmental benefits) are theorised to cause the higher-order construct (PCB). A prerequisite for establishing a valid higher-order construct is the inclusion of several indicators for each lower-order construct.

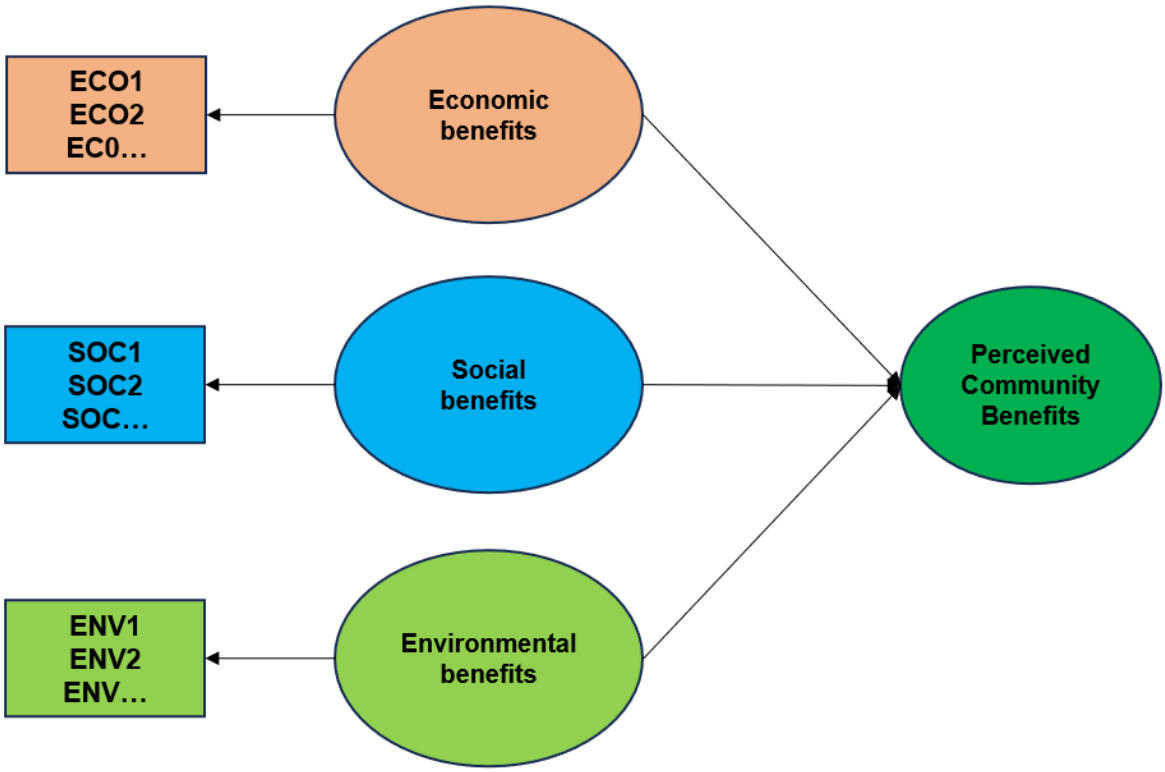


Fig. N-7. Reflective-formative construct for perceived community benefits.

Effect of mediation in the DHAM for each exogenous construct

Table N-12. Difference in beta coefficients between endogenous constructs.

Construct	Domestic Hydrogen Acceptance (β coefficient)	Willingness to Adopt Domestic Hydrogen (β coefficient)	Absolute difference	Percentage difference (%)
AWR	0.019	0.012	0.007	0.368
KNW	0.019	0.005	0.014	0.737
PT	0.198	0.124	0.074	0.374
PP	0.212	0.133	0.079	0.373
SP	0.058	0.037	0.021	0.362
PDI	0.092	0.058	0.034	0.370
PSC	0.057	0.036	0.021	0.368
PCB	0.276	0.173	0.103	0.373
PE	0.218	0.137	0.081	0.372
NE	0.138	0.087	0.051	0.370

Model 2: Willingness to Adopt Domestic Hydrogen (direct effects)

Measurement model assessment for Model 2

Table N-13. Assessment of reliability, convergent validity, and multicollinearity.

Construct	CA	CR (P_A)	CR (P_C)	AVE	VIF
Awareness	0.797	0.802	0.907	0.831	1.346
Knowledge	n/a	n/a	n/a	n/a	1.435
Public Trust	0.864	0.905	0.900	0.643	1.513
Production Perceptions	0.816	0.849	0.870	0.577	1.592
Safety Perceptions	0.918	0.920	0.939	0.754	1.580
Perceived Disruptive Impacts	0.758	0.849	0.855	0.667	1.253
Perceived Socio-economic Costs	0.730	0.730	0.881	0.788	1.424
Perceived Community Benefits	0.808	0.808	0.886	0.722	2.056
Positive Emotions	0.881	0.883	0.918	0.737	1.464
Negative Emotions	0.869	0.916	0.906	0.708	1.407
Willingness to Adopt Domestic Hydrogen	0.934	0.934	0.958	0.883	n/a

Table N-14. Heterotrait-monotrait results for assessment of discriminant validity.

	AWR	KNW	NE	PCB	PDI	PSC	PE	PP	PT	SP	WTA
AWR											
KNW	0.537										
NE	0.080	0.113									
PCB	0.111	0.086	0.256								
PDI	0.064	0.094	0.511	0.197							
PSC	0.073	0.161	0.530	0.437	0.392						
PE	0.294	0.297	0.115	0.527	0.153	0.249					
PP	0.247	0.244	0.237	0.638	0.193	0.329	0.404				
PT	0.235	0.250	0.118	0.520	0.144	0.122	0.428	0.473			
SP	0.088	0.135	0.125	0.640	0.036	0.159	0.403	0.413	0.488		
WTA	0.279	0.297	0.240	0.514	0.219	0.287	0.674	0.418	0.348	0.368	

Table N-15. Results for the Fornell Larcker test.

	AWR	KNW	NE	PCB	PDI	PSC	PE	PP	PT	SP	WTA
AWR	0.911										
KNW	0.479	1.000									
NE	0.067	0.098	0.841								
PCB	0.090	0.077	-0.235	0.850							
PDI	0.023	0.057	0.408	-0.162	0.817						
PSC	0.055	0.138	0.427	-0.339	0.278	0.887					
PE	0.248	0.279	-0.098	0.446	-0.138	-0.201	0.859				
PP	0.208	0.218	-0.214	0.532	-0.156	-0.279	0.353	0.760			
PT	0.197	0.231	-0.080	0.452	-0.127	-0.059	0.386	0.407	0.802		
SP	0.075	0.130	-0.130	0.551	-0.029	-0.130	0.363	0.350	0.438	0.868	
WTA	0.241	0.287	-0.243	0.447	-0.198	-0.237	0.612	0.379	0.329	0.341	0.940

Table N-16. Cross loadings results for establishing discriminant validity.

	AWR	KNW	NE	PCB	PDI	PSC	PE	PP	PT	SP	WTA
AWR1	**0.921**	0.442	0.054	0.098	0.040	0.039	0.240	0.206	0.182	0.065	0.230
AWR2	**0.902**	0.431	0.068	0.064	0.000	0.063	0.210	0.172	0.176	0.073	0.208
PCB1	0.087	0.078	-0.129	**0.850**	-0.103	-0.219	0.374	0.415	0.393	0.474	0.359
PCB2	0.075	0.069	-0.161	**0.869**	-0.097	-0.270	0.373	0.398	0.399	0.521	0.381
PCB3	0.068	0.050	-0.300	**0.831**	-0.208	-0.368	0.389	0.538	0.362	0.411	0.398
PDI1	0.087	0.150	0.346	-0.092	**0.644**	0.263	-0.043	-0.096	-0.023	0.008	-0.082
PDI2	0.011	0.033	0.336	-0.130	**0.878**	0.206	-0.120	-0.128	-0.115	-0.029	-0.174
PDI3	0.000	0.019	0.354	-0.163	**0.904**	0.250	-0.145	-0.150	-0.137	-0.035	-0.197
KNW	0.479	**1.000**	0.098	0.077	0.057	0.138	0.279	0.218	0.231	0.130	0.287
NE1	0.044	0.102	0.697	-0.090	0.277	0.293	0.053	-0.136	0.008	-0.014	-0.062
NE2	0.052	0.054	0.907	-0.205	0.391	0.377	-0.119	-0.183	-0.080	-0.146	-0.246
NE3	0.060	0.085	0.906	-0.202	0.353	0.379	-0.085	-0.186	-0.062	-0.135	-0.218
NE4	0.067	0.117	0.838	-0.239	0.338	0.381	-0.086	-0.204	-0.087	-0.078	-0.207
PE1	0.195	0.243	-0.055	0.393	-0.106	-0.182	**0.869**	0.304	0.331	0.306	0.523
PE2	0.186	0.239	-0.088	0.328	-0.117	-0.138	**0.838**	0.281	0.306	0.299	0.489
PE3	0.248	0.270	-0.078	0.363	-0.122	-0.141	**0.868**	0.279	0.339	0.309	0.547
PE4	0.219	0.206	-0.115	0.446	-0.128	-0.227	**0.860**	0.346	0.346	0.331	0.541
PP1	0.077	0.143	0.014	0.257	0.035	-0.015	0.159	0.541	0.279	0.272	0.155
PP2	0.173	0.144	-0.215	0.446	-0.164	-0.279	0.290	**0.819**	0.275	0.232	0.324
PP3	0.149	0.094	-0.264	0.480	-0.194	-0.309	0.290	**0.810**	0.285	0.259	0.309
PP4	0.207	0.234	-0.160	0.447	-0.127	-0.229	0.324	**0.823**	0.397	0.316	0.350
PP5	0.153	0.220	-0.101	0.342	-0.064	-0.129	0.237	**0.766**	0.322	0.279	0.249
PSC1	0.055	0.130	0.387	-0.282	0.252	**0.886**	-0.178	-0.284	-0.054	-0.103	-0.209
PSC2	0.043	0.114	0.371	-0.320	0.241	**0.889**	-0.178	-0.211	-0.051	-0.129	-0.212
PT1	0.153	0.183	-0.086	0.352	-0.098	-0.040	0.299	0.335	**0.858**	0.354	0.261
PT2	0.177	0.190	-0.180	0.478	-0.180	-0.159	0.384	0.426	**0.841**	0.374	0.363
PT3	0.169	0.200	0.014	0.328	-0.055	0.026	0.308	0.271	**0.816**	0.388	0.233
PT4	0.103	0.108	-0.061	0.374	-0.092	-0.075	0.268	0.317	**0.779**	0.329	0.204
PT5	0.181	0.254	0.080	0.212	-0.036	0.089	0.245	0.227	**0.708**	0.306	0.196
SP1	0.065	0.093	-0.129	0.512	-0.034	-0.136	0.308	0.322	0.379	**0.883**	0.297
SP2	0.065	0.096	-0.145	0.491	-0.027	-0.116	0.301	0.296	0.357	**0.870**	0.289
SP3	0.050	0.109	-0.100	0.466	-0.029	-0.131	0.306	0.293	0.374	**0.866**	0.291
SP4	0.065	0.127	-0.095	0.437	-0.034	-0.087	0.316	0.295	0.382	**0.838**	0.283
SP5	0.081	0.138	-0.095	0.482	-0.005	-0.096	0.341	0.313	0.409	**0.883**	0.320
WTA1	0.243	0.286	-0.203	0.419	-0.183	-0.203	0.580	0.356	0.305	0.311	**0.941**
WTA2	0.230	0.268	-0.237	0.422	-0.192	-0.229	0.577	0.345	0.294	0.325	**0.946**
WTA3	0.206	0.256	-0.243	0.420	-0.182	-0.235	0.570	0.367	0.327	0.326	**0.931**

Structural model assessment for Model 2

Table N-17. Results of path analysis and hypothesis testing

	β coefficient (SD)	***t*-statistic**	***ρ*-value**	f^2	Result
H1: AWR → (+) WTA	0.055 (0.020)	2.741	0.006	0.004	Accepted
H2: KNW → (+) WTA	0.131 (0.020)	6.646	<0.001	0.023*****	Accepted
H3: PT → (+) WTA	-0.004 (0.022)	0.181	0.856	0.000	Rejected
H4: PP → (+/-) WTA	0.052 (0.022)	2.399	0.016	0.003	Accepted
H5: SP → (+/-) WTA	0.047 (0.023)	2.105	0.035	0.003	Accepted
H6: PDI → (-) WTA	-0.052 (0.020)	2.581	0.010	0.004	Accepted
H7: PSC → (-) WTA	-0.033 (0.021)	1.544	0.123	0.001	Rejected
H8: PCB → (+) WTA	0.133 (0.025)	5.224	<0.001	0.016	Accepted
H9: PE → (+) WTA	0.442 (0.021)	21.266	<0.001	0.250******	Accepted
H10: NE → (-) WTA	-0.133 (0.021)	6.262	<0.001	0.023*****	Accepted

****** Medium-sized effect = 0.15–0.35
***** Small effect size (i.e. 0.02–0.15)
No effective size = <0.02

Assessment of out-of-sample predictive power

Table N-18. Results of predictive power using $PLS_{predict}$.

	Q^2predict	**PLS-SEM_RMSE**	**PLS-SEM_MAE**	**LM_RMSE**	**LM_MAE**
WTA1	0.405	0.774	0.608	0.777	0.610
WTA2	0.409	0.780	0.613	0.785	0.616
WTA3	0.400	0.805	0.634	0.810	0.633

Table N-19. CVPAT benchmark and results for predictive ability test.

			PLS-SEM vs. Indicator average (IA)		
Construct	**PLS loss**	**IA loss**	**Average loss difference**	**t value**	***p* value**
WTA	0.618	1.039	-0.421	15.934	<0.001
			PLS-SEM vs. Linear Model (LM)		
	PLS loss	**LM loss**	**Average loss difference**		
WTA	0.618	0.626	-0.007	2.007	0.045

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APPENDIX O. Heterogenous preferences for living in a hydrogen home: a multigroup analysis of UK households (chapter 5)

Evidence on public perceptions of hydrogen from Australia

In 2021, Martin et al. [1] found no significant differences in levels of hydrogen support between respondents identifying with one of Australia's three national parties (Liberal/National, Labour, and Greens), although support proved lower among respondents corresponding to 'other' political party preferences (i.e. Not Liberal/National, Labour or Greens). The authors concluded that the hydrogen industry should therefore garner bi-partisan public support [1].

However, no speculation was made as to the potential relevance of an association between apolitical beliefs and lower support for the national hydrogen economy or wider energy transition. In terms of gender, males proved significantly more supportive of hydrogen, although this disparity closed considerably following information provision [1]. This result may infer a more cautious or sceptical attitude among female respondents in absence of information, whereas males have a stronger predisposition to supporting emerging hydrogen energy technologies [2–4].

Heterogenous energy preferences in the United Kingdom

Roddis and colleagues [5] found that the Southwest and Eastern England had higher levels of support for most energy types, whereas Scotland and London presented consistently lower approval rates, which reflects an approximate North-South divide. Nevertheless, it was concluded that age and concern for climate change were stronger predictors of public acceptance than regional location [5]. Notably, divergence was also observed between urban and rural locations for specific technologies, while citizens most and least directly exposed to energy technologies[1] (i.e. Scotland and London) had the lowest support levels [5]. The contribution of Roddis et al. [5] reinforces the need to recognise that public perceptions of energy technologies may be characterised by different degrees of consumer heterogeneity.

[1] Also including onshore and offshore wind, wave/tidal, and biomass.

Survey questions and supporting literature

Table 0-1 provides full details of the survey questions pertaining to each construct and its respective indicators, as well as the scales employed, in addition to the supporting literature for deriving each item.

Table 0-1. Questionnaire details and literature sources.

Construct	Indicator	Question items and framing	Scale	Supporting literature
Boiler Performance (BLR)		Please evaluate the following statements about a hydrogen boiler**:**	0–10: Low expectation – High expectation	[6–13]
	BLR1	I expect a hydrogen boiler to provide a higher level of thermal comfort than a natural gas boiler (i.e. satisfactory level and distribution of heat)		
	BLR2	I expect a hydrogen boiler to be more energy efficient than a natural gas boiler		
	BLR3	I expect a hydrogen boiler to be easier to operate than a natural gas boiler		
	BLR4	I expect a hydrogen boiler to provide a smarter heating system than a gas boiler		
Hob Performance (HOB)		Please evaluate the following statements about a hydrogen hob:	0–10: Low expectation – High expectation	[6,7]
	HOB1	I expect a hydrogen hob to perform more efficiently than a natural gas hob		
	HOB2	I expect a hydrogen hob to provide better cooking control than a natural gas hob		
	HOB3	I expect a hydrogen hob to be easier to maintain and clean than a natural gas hob		
	HOB4	I expect a hydrogen hob to provide a smarter cooking system than a natural gas hob		
Financial Perceptions (FP)	FP1	What is your expectation for the purchasing price of a hydrogen boiler compared to a gas boiler?	1–5: Significantly cheaper –	[14–19]

	FP2	What is your expectation for the purchasing price of a hydrogen hob compared to a gas hob?	Significantly more expensive	
	FP3	What is your expectation when considering potential energy bills for domestic hydrogen compared to natural gas?		
Perceived socio-economic Costs (PSC)		To what extent do you agree or disagree with the following statements:	1–5: Strongly disagree – Strongly agree	[14,15,18,20–22]
	PSC1	Switching from natural gas to hydrogen will have a negative impact on UK energy security (i.e. reliability of energy supply)		
	PSC2	Switching from natural gas to hydrogen will lead to higher levels of fuel poverty across the UK		
Safety Perceptions (SP)		Please evaluate your current safety perceptions of hydrogen compared to natural gas for the following:	0–10: Less safe – More safe	[1,6,15,23–28]
	SP1	Hydrogen boilers		
	SP2	Hydrogen hobs		
	SP3	Hydrogen pipelines (i.e. transport/transmission)		
	SP4	Underground storage of hydrogen gas		
	SP5	Overall, how do you perceive the safety level of hydrogen compared to natural gas in terms of production, storage, transportation, and domestic use?		
Production Perceptions (PP)	PP1	What is your attitude towards the UK government supporting blue hydrogen production in the short-term (i.e. up to 2030)?	0–10: Opposed – Supportive	[1,3,23,29–31]
	PP2	What is your attitude towards the UK government supporting blue hydrogen production over the long-term (i.e. after 2030)?		
	PP3	What is your attitude towards the UK government supporting green hydrogen production in the short-term (i.e. up to 2030)?		
	PP4	What is your attitude towards the UK government supporting green hydrogen production over the long-term (i.e. after 2030)?		

	PP5	How do you feel about the government's twin-track strategy? (i.e. with a role for blue and green hydrogen)		
Domestic Hydrogen Adoption Potential (ADPT)				
	ADPT1	What is your level of willingness to switch to a hydrogen boiler before 2030?	1–5: Not willing at all – Extremely willing	[18,32–34]
	ADPT2	What is your level of willingness to switch to a hydrogen hob before 2030?		
	ADPT3	What is your level of willingness to switch to a hydrogen home before 2030? (i.e. both hydrogen heating and cooking)		
	ADPT4	What is your expectation for hydrogen homes delivering economic benefits such as job opportunities and income security?	0–10: Low – High expectation	[4,14,35–38]
	ADPT5	What is your expectation for hydrogen homes delivering social benefits such as reduced levels of fuel poverty and improved health?		
	ADPT6	What is your expectation for hydrogen homes delivering environmental benefits such lower carbon emissions and better air quality?		

Sample characteristics and comparison to UK population

Table 0-2 describes the breakdown of each consumer sub-group composing our survey sample (N =1845). The ideal target was to secure an equally balanced representation among three of sub-groups (i.e. MEG, VEG, FSG), alongside a larger Baseline Group (BLG) of ~40%. Higher occurrences of incomplete answers and straight-lining responses resulted in a final sample of 677 for the BLG (~36.7%). During the data collection, the Very Engaged Group (VEG) proved harder to reach, leading to partial under-representation (N = 331, 17.9%). By comparison, the Moderately Engaged Group (MEG) was easier to secure and somewhat over-represented (24.8%). Finally, the Fuel Stress Group (FSG) was in line with the original quotas (20.5%).

Table 0-2. Consumer sub-groups composing the survey sample.

Socio-demographic variable	BLG (N = 677)	MEG (N = 458)	VEG (N = 331)	FSG (N = 379)	Standard deviation	Full sample (N = 1845)	UK population	Difference (%)
Age								
18-34	34.1	31.7	38.7	39.8	3.82	35.5	32.6	+2.9
35-54	41.7	37.3	33.2	42.2	4.22	39.2	30.6	+8.6
55+	24.2	31.0	28.1	17.9	5.67	25.3	36.8	-11.5
Gender								
Male	36.8	42.6	56.5	47.2	8.32	43.9	48.8	-4.9
Female	63.2	57.4	43.5	52.8	8.32	56.1	51.2	+4.9
Other								
Housing tenure								
Owned outright	34.7	36.0	47.4	34.3	6.24	37.2	57.1	-19.9
Mortgage owner	65.3	64.0	52.6	65.7	6.24	62.8	42.9	+19.9
Housing type								
Flat, apartment or bungalow	12.3	9.2	16.6	12.4	3.04	12.3	30.0	-17.7
Detached house	29.1	30.8	30.8	25.3	2.59	29.1	18.0	+11.1
Semi-detached house	36.9	42.1	35.3	39.6	3.00	38.5	25.0	+13.5
Terrace house	21.7	17.9	17.2	22.7	2.73	20.2	27.0	-6.8
No. of occupants								
1	11.7	10.0	9.1	7.9	1.60	10.0	n/a	
2	30.6	32.3	26.0	30.6	2.70	30.2	n/a	

3+	57.8	57.6	65.0	61.5	3.51	59.8	n/a	
Education level								
GCSE/O-Level or lower	24.2	17.9	18.7	24.5	3.51	21.7	n/a	
Vocational/NVQ	27.0	25.8	17.5	23.2	4.23	24.2	n/a	
Postgraduate qualification	17.7	23.1	26.3	21.4	3.58	21.4	n/a	
Degree or equivalent	31.0	33.2	37.5	30.9	3.09	32.7	n/a	
Annual income bracket (before tax)								
Less than £23,500	30.1	27.1	16.9	28.0	5.89	26.6	n/a	
More than £23,500 but less than £31,500	20.7	19.4	16.9	26.1	3.88	20.8	n/a	
More than £31,500 but less than £41,500	18.9	18.6	19.0	19.0	0.19	18.9	n/a	
More than £41,500 but less than £62,500	20.7	23.1	23.9	19.8	1.94	21.7	n/a	
More than £62,500	9.6	11.8	23.3	7.1	7.16	12.1	n/a	
Location								
Southwest and Wales	11.7	15.3	11.5	11.6	1.85	12.5	13.4	-0.9
Midlands and East of England	27.8	25.8	22.1	25.3	2.36	25.7	26.2	-0.5
Southeast and London	26.0	28.6	35.3	22.2	5.52	27.5	27.2	+0.3
North of England and Scotland	34.6	30.3	31.1	40.9	4.83	34.2	33.0	+1.2
Area type								
Inner City or industrial	6.5	7.6	12.7	11.6	3.01	8.9	n/a	
Suburban	54.7	56.3	44.7	48.8	5.36	52.1	n/a	
Urban	19.1	17.7	28.4	24.8	4.99	21.6	n/a	
Rural	19.8	18.3	14.2	14.8	2.71	17.4	n/a	

Source: Authors' compilation based on [39–41].

[a] n/a denotes the decision to exclude these variables when setting quotas, therefore population data is not reported here.

The sample was composed of respondents owning a property outright (57.1%) and mortgage owners (42.9%), following the logic that home ownership will raise the stakes for decision-making and consumer engagement regarding domestic hydrogen [42]. Moreover, all respondents were users of natural gas boiler and hobs; attributing at least moderate levels of important to being able to choose these technologies, while having at least moderate levels of financial involvement in the decision-making process [6,10,43].

The sampling decision reflects the under-representation of respondents living in a bungalow, flat, or apartment within the sample (12.3% compared to the national average of 30.0%). Relatedly, in the Welsh context, Thomas et al.[44] reported that "bungalows (11.5%) and flats (11%) represent a smaller proportion of the overall housing stock, with the latter less reliant on gas heating due to safety and planning regulation." Notably, 40.9% of fuel stressed respondents in this study are from the North of England and Scotland, compared to the sample average of 34.2%, which reflects the decision to adjust the location filter for the FSG to be broadly nationally representative of fuel poverty in the UK [45].

Fig. 0-1 reports the composition of the sample in relation to levels of financial involvement in financial decision-making, and the level of importance attributed towards having a choice about household heating and cooking technologies.

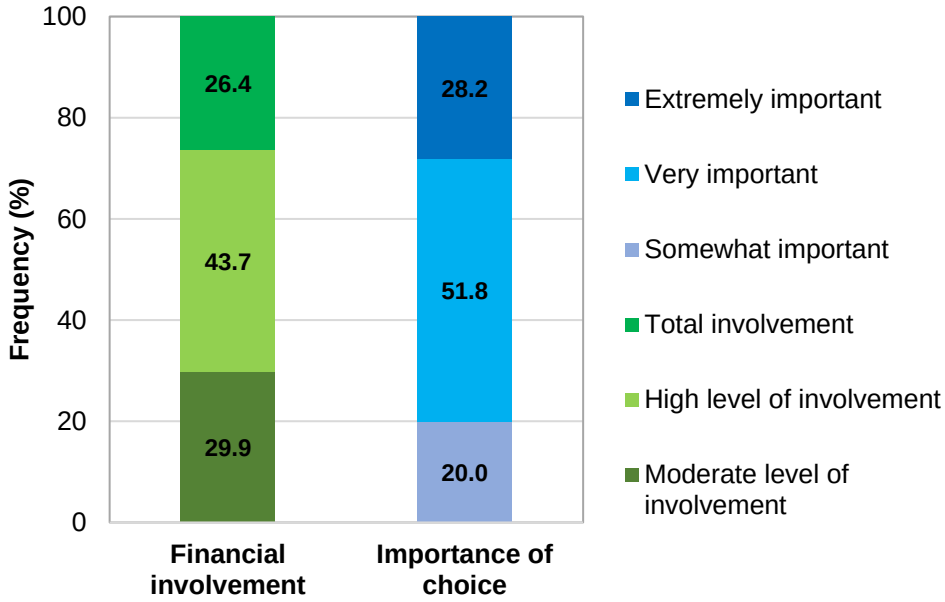


Fig. 0-1. Financial involvement in appliance purchase and choice perceptions across sample.

Table 0-3. Seminal technology acceptance studies employing multigroup analysis or moderation analysis.

Author and year of study	Empirical focus and location of study	Research method and sample size	Theoretical foundation(s)	Application of MGA/moderation analysis to structural equation modelling
Lin [46] 2011	• Examines the antecedents of attitude and behavioural intention towards adopting (or continuing to use) mobile banking • Taiwan	• Paper-based questionnaire • N = 368	• DoI theory and knowledge-based trust model	• Group 1 = Potential customers (N = 177) • Group 2 = Repeat customers (N = 191)
Thakur and Srivastava [47] 2014	• Examines the antecedents of usage intention for mobile payments • India	• Paper-based questionnaire • N = 774	• TAM • UTAUT	• Group 1: Users • Group 2: Non-users[a]
Leong et al. [48] 2013	• Examines the determinants of mobile credit card adoption • Malaysia	• Self-administered questionnaire • N = 262	• Extended TAM	• Gender (male, female) • Age (younger, older) • Experience (low, high) • Usage (low, high)
Farooq et al. [49] 2020	• Investigates the impact of online information on the individual-level intention to voluntarily self-isolate during the COVID-19 pandemic • Finland	• Online survey • N = 225	• Protection motivation theory[b]	• Group 1a: Living alone (N = 122) • Group 1b: Living with others (N = 109) • Group 2a: Social media as primary information channel (N = 119) • Group 2b: Other information channels (N = 106)
Tarhini et al. [50] 2017	• Examines the effects of individual-level culture on the adoption and acceptance of e-learning tools by students • Lebanon	• Online survey • N = 569	• Extended TAM	• Power distance[c] • Cultural values (masculinity vs femininity) • Uncertainty avoidance[d] • Individualism/collectivism
Tan et al. [51] 2014	• Investigates the factors influencing mobile credit card adoption • Malaysia	• Self-administered questionnaire • N = 156	• Extended TAM	• Gender (male, female)

Barbarossa & De Pelsmacker [52] 2016	• Examiners the drivers and barriers towards purchasing eco-friendly products • Italy	• Self-administered questionnaire • N = 926	• Social dilemma theory • Psychological egoism theory	• Group 1: Green consumers (N = 453) • Group 2: Non-green consumers (N = 473)
Krasnova et al. [53] 2012	• Examines the role of culture in individual self-disclosure decisions among users of social networking sites • United States • Germany	• Online survey • N = 375	• Privacy calculus perspective[e]	• Group 1: American users (N = 237) • Group 2: German users (N = 138)[f]
Kong et al. [54] 2013	• Examines effects of loneliness and self-esteem for the relationship between social support and life satisfaction among college students	• Self-administered questionnaire • N = 389	• Attachment and stress theory[g]	• Group 1: Female students (N = 260) • Group 2: Male students (N = 129)
Pappas et al. [55]	• Examines the moderating role of experience on repurchase intention among online shoppers • Greece	• Online survey and self-administered questionnaire • N = 393	• UTAUT • Expectation confirmation theory • Social cognitive theory	• Group 1: Low-experienced customers (N = 214) • High-experienced customers (N = 179)

[a] Sample size not provided.

[b] The theory examines motivational reasons for adoption protective measures and divides the causes into threat appraisal and coping appraisal.

[c] The extent to which individuals expect and accept differences in power between different people.

[d] The extent to which ambiguities and uncertainties are tolerated.

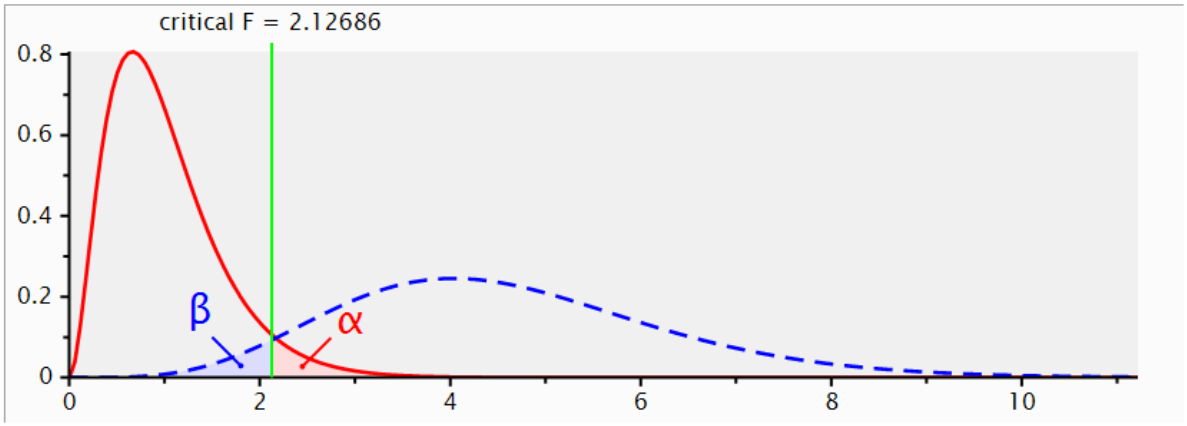
[e] Rooted in social exchange theory.

[f] Users were national of each country. In the case of Germany, 99 foreign respondents were excluded from the sample.

[g] Rooted in theories related to attachment and stress.

Statistical tests for validating sample size specifications

Fig. 0-2 and Fig. 0-3 provide results on sample size requirements for testing effect sizes. We used G*Power software to verify the parameters. Since our sample was relatively large (N = 1845), it was suitable for PLS-SEM, however, we checked the results from G*Power to clarify the reliability of (small) effect sizes, as described in Section 5.6.2.



Input Parameters

Determine => Effect size f²	0.065
α err prob	0.05
Power (1−β err prob)	0.95
Number of predictors	6

Output Parameters

Noncentrality parameter λ	21.3200000
Critical F	2.1268600
Numerator df	6
Denominator df	321
Total sample size	328
Actual power	0.9505145

Fig. 0-2. Power test to determine the minimum sample size for an effect size of 0.02 at 95% significance.

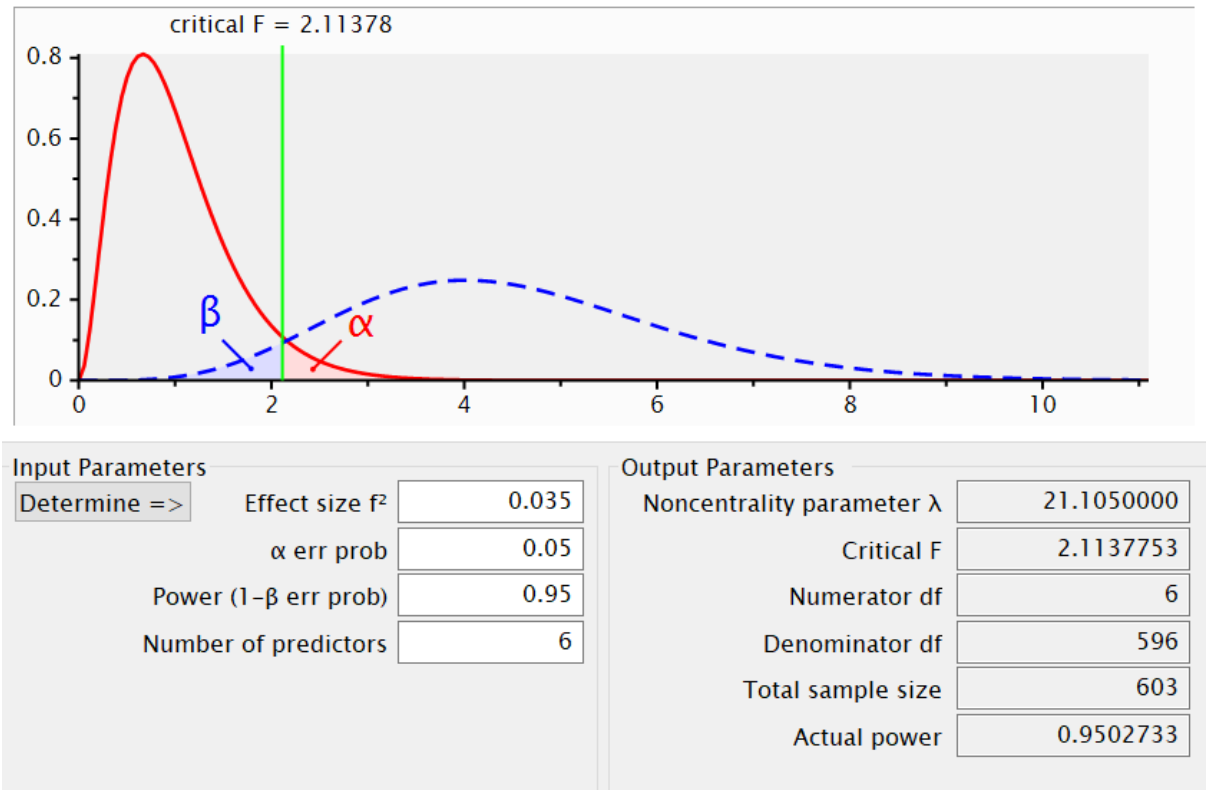


Fig. 0-3. Power test to determine the minimum sample size for an effect size of 0.02 at 95% significance.

Table 0-4 tests each indicator for common method bias (CMB) across the full sample, which was ruled out by the results. The ranges for CMB held consistent across the sub-samples.

Table 0-4. Harman single factor test for common method bias.

Total Variance Explained						
Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	8.519	29.376	29.376	8.519	**29.376**	**29.376**
2	2.868	9.89	39.265			
3	2.322	8.006	47.272			
4	2.05	7.069	54.341			
5	1.627	5.611	59.952			
6	1.58	5.447	65.399			
7	0.944	3.257	68.656			
8	0.911	3.143	71.799			
9	0.784	2.703	74.501			
10	0.721	2.488	76.989			
11	0.612	2.109	79.099			
12	0.556	1.918	81.017			
13	0.501	1.726	82.743			
14	0.472	1.626	84.369			
15	0.435	1.502	85.871			
16	0.424	1.462	87.333			
17	0.414	1.426	88.759			
18	0.372	1.281	90.041			
19	0.358	1.233	91.274			
20	0.339	1.168	92.443			
21	0.317	1.094	93.537			
22	0.307	1.057	94.594			
23	0.293	1.01	95.604			
24	0.285	0.984	96.587			
25	0.24	0.827	97.414			
26	0.218	0.75	98.165			
27	0.196	0.678	98.842			
28	0.19	0.654	99.496			
29	0.146	0.504	100			
Extraction Method: Principal Component Analysis.						

Skewness and kurtosis

Table 0-5 reports the skewness and kurtosis for each indicator to verify the suitability of PLS-SEM, as discussed in Section 5.6.2.

Table 0-5. Results for skewness and kurtosis.

	BLG (N = 677)		MEG (N = 458)		VEG (N = 331)		FSG (N = 379)	
	Kurtosis	**Skewness**	**Kurtosis**	**Skewness**	**Kurtosis**	**Skewness**	**Kurtosis**	**Skewness**
SP1	-0.127	-0.072	-0.173	-0.189	-0.266	-0.423	-0.013	-0.113
SP2	-0.147	-0.126	-0.262	-0.212	-0.016	-0.605	0.080	-0.098
SP3	-0.053	-0.055	-0.286	-0.161	-0.298	-0.515	-0.033	-0.184
SP4	-0.165	-0.016	-0.373	-0.098	-0.310	-0.597	-0.064	-0.191
SP5	-0.026	-0.141	-0.303	-0.296	-0.002	-0.590	0.500	-0.350
BLR1	-0.211	-0.356	-0.139	-0.530	0.522	-0.967	-0.373	-0.496
BLR2	0.513	-1.063	1.379	-1.333	1.961	-1.455	0.418	-1.098
BLR3	-0.384	-0.272	-0.428	-0.314	-0.305	-0.649	-0.530	-0.436
BLR4	0.076	-0.796	0.169	-0.840	0.905	-1.195	0.011	-0.883
HOB1	-0.007	-0.539	0.114	-0.656	0.445	-0.875	-0.366	-0.343
HOB2	0.177	-0.288	-0.135	-0.372	0.020	-0.580	0.095	-0.282
HOB3	-0.210	-0.289	-0.329	-0.416	-0.079	-0.614	-0.287	-0.157
HOB4	0.040	-0.424	0.157	-0.606	0.109	-0.613	-0.248	-0.360
FP1	1.147	-1.233	0.449	-0.892	-0.070	-0.727	0.217	-0.883
FP2	1.171	-1.173	0.254	-0.709	0.035	-0.653	-0.112	-0.692
FP3	-1.053	-0.034	-0.904	0.088	-0.919	-0.131	-0.905	0.061
PSC1	-0.203	0.294	-0.418	0.362	-0.826	0.371	-0.430	0.153
PSC2	-0.297	0.169	-0.404	0.099	-0.801	0.094	-0.569	0.011
PP1	-0.017	0.014	-0.008	-0.324	-0.682	-0.405	0.258	-0.178
PP2	-0.391	-0.041	-0.504	-0.339	0.245	-0.761	-0.119	-0.277
PP3	-0.611	-0.190	-0.349	-0.583	1.512	-1.207	-0.145	-0.356
PP4	0.316	-0.109	0.276	-0.301	0.293	-0.581	0.380	0.124
PP5	0.050	-0.028	0.294	-0.174	-0.099	-0.388	0.498	0.126
ADPT1	-0.131	0.190	-0.418	0.146	-0.324	-0.245	-0.154	-0.094

ADPT2	-0.149	0.339	-0.405	0.187	-0.493	-0.217	-0.167	0.060
ADPT3	-0.028	0.346	-0.473	0.224	-0.653	-0.220	-0.388	0.104
ADPT4	0.054	-0.307	0.177	-0.430	1.240	-0.893	0.128	-0.472
ADPT5	-0.091	-0.358	0.252	-0.445	1.027	-0.937	0.106	-0.459
ADPT6	0.020	-0.512	-0.048	-0.568	0.198	-0.761	-0.016	-0.408

Limitations of the Kruskal-Wallis H test

The Kruskal-Wallis (K-W) H test can be used to support behavioural and social science research [46] by identifying group-specific differences when the samples are independent [47], as is the case in this study. For example, Vibrans et al. [48] applied the K-W test when examining heterogeneity among potential solar PV adopters in Germany, as a complementary method to PLS-MGA. Nevertheless, non-parametric tests such as K-W are not without their limitations [46,49] such as potentially lower statistical power [50]. Furthermore, post-hoc tests are required to determine where statistically significant differences are detected [46] and to estimate effect sizes, rendering the K-W test as a means for supporting descriptive research and preliminary hypothesis testing [50]. In response, some researchers have proposed modified versions of the K-W test to increase robustness and statistical accuracy [49].

Kruskal-Wallis H Test results for adoption factors

Safety Perceptions

In terms of safety perceptions, the VEG expressed the most positive outlook (M = 6.59), followed by the MEG (M = 5.87), the FSG (M = 5.75), and finally, the BLG (M = 5.55). Notably, the VEG registered a more positive perception across all safety metrics compared to other sub-groups, which also held true when comparing the MEG to the BLG and FSG. Based on these patterns, technology and environmental engagement is positively correlated with confidence in hydrogen safety. A K-W test was performed after forming a composite score from the five safety indicators, which supported the presence of consumer heterogeneity: H (3, N = 1845) = 85.97, $p < 0.001$. The groups rank as follows (highest to lowest): VEG: Md = 1156; MEG: Md = 923; FSG: Md = 887; BLG: Md = 829.

Technology Perceptions

Regarding technological perceptions, the VEG attributed the strongest positive expectation to boiler performance (M = 7.54), followed by the FSG (M = 7.10), MEG (M = 6.99) and BLG (M = 6.81). The VEG also reflected the highest level of confidence in hydrogen cooking (M = 6.81), followed by the MEG (M = 6.22), the FSG (M = 6.15), and the BLG (M = 5.94). Overall, the VEG emerges as the consumer segment with highest level of expectancy regarding the relative advantage of hydrogen appliances, while the BLG is the least conservative sub-group when compared at the descriptive level. Consequently, a K-W test detected group-specific differences regarding

perceptions of boiler performance (composite score): H (3, N = 1845) = 31.57, p < 0.001. The groups rank as follows (highest to lowest): VEG: Md = 1054; FSG: Md = 939; MEG: Md = 916; BLG: Md = 855. A comparable result is likewise reported for hob performance (composite score): H (3, N = 1845) = 49.12, p < 0.001. The groups rank as follows (highest to lowest): VEG: Md = 1094; MEG: Md = 932; FSG: Md = 899; BLG: Md = 846.

Financial Perceptions

In terms of financial perceptions, the BLG held the most negative perspective or highest level of concern across all three metrics (M = 7.69), followed by the MEG (M = 7.41), FSG (M = 7.25) and VEG (M = 7.21). As a result, consumer heterogeneity was identified: H (3, N = 1845) = 29.93, p < 0.001. The groups rank as follows (least negative to most negative financial perception): VEG: Md = 848; FSG: Md = 862; MEG: Md = 901; BLG: Md = 1008. The expectation that hydrogen boilers would be significantly more expensive to purchase than natural gas boilers proved largest across the sample (FP1: M = 8.08) and for all sub-groups. Nevertheless, respondents perceived the purchasing price of each appliance to be relatively comparable. For example, perceptions proved near equivalent in the case of the BLG: Boiler: M = 8.36; Hob: M = 8.32. In line with previous findings [14], there was less expectation across the sample that a switch to hydrogen would adversely impact energy bills FP3: M = 6.28).

Perceived Socio-economic Costs

At the macro-economic level, the FSG relayed the most negative outlook across both metrics (PSC1: M = 5.82; PSC2: M = 6.12). Consequently, the FSG represents the most concerned sub-group (M = 5.97) in respect to perceived socio-economic impacts, followed by the BLG (M = 5.82), VEG (M = 5.64), and MEG (M = 5.52). In view of the FSG expressing higher levels of socio-economic concern, group-specific differences were identified: H (3, N = 1845) = 10.540, p = 0.014. The groups rank as follows (least negative to most negative socio-economic perception): VEG: Md = 865; MEG: Md = 888; BLG: Md = 949; FSG: Md = 967.

Production Perceptions

Finally, regarding production perceptions, the VEG proved outright the most supportive consumer segment (M = 7.24), followed by the MEG (M = 6.60), FSG (M =

6.02), and BLG (*M* = 5.93). As a result, the data suggests technology and environmental engagement is positively associated with support for the twin-track approach. Moreover, in view of descriptive results for each production pathway, support is strongest for green hydrogen production [77]. The mean score for PP1 and PP2 (blue) = 6.17, while the mean score for PP3 and PP4 (green) = 6.86 across the sample. In this case, a substantial level of consumer heterogeneity is observed: *H* (3, N = 1845) = 207.36, $p < 0.001$. The groups rank as follows (highest to lowest): VEG: *Md* = 1241; MEG: *Md* = 1019; FSG: *Md* = 796; BLG: *Md* = 774.

Distribution of accepters and rejecters of hydrogen homes

Fig. 0-4 provides an alternative representation of the data presented in Fig. 5-9 by adjusting the results to the sample size of each group. Therefore, 15.8% of respondents in the BLG corresponded to a position of outright rejection (i.e. 107/677), while 25.4% of respondents in the VEG could be considered outright 'accepters' of hydrogen homes (i.e. 84/331).

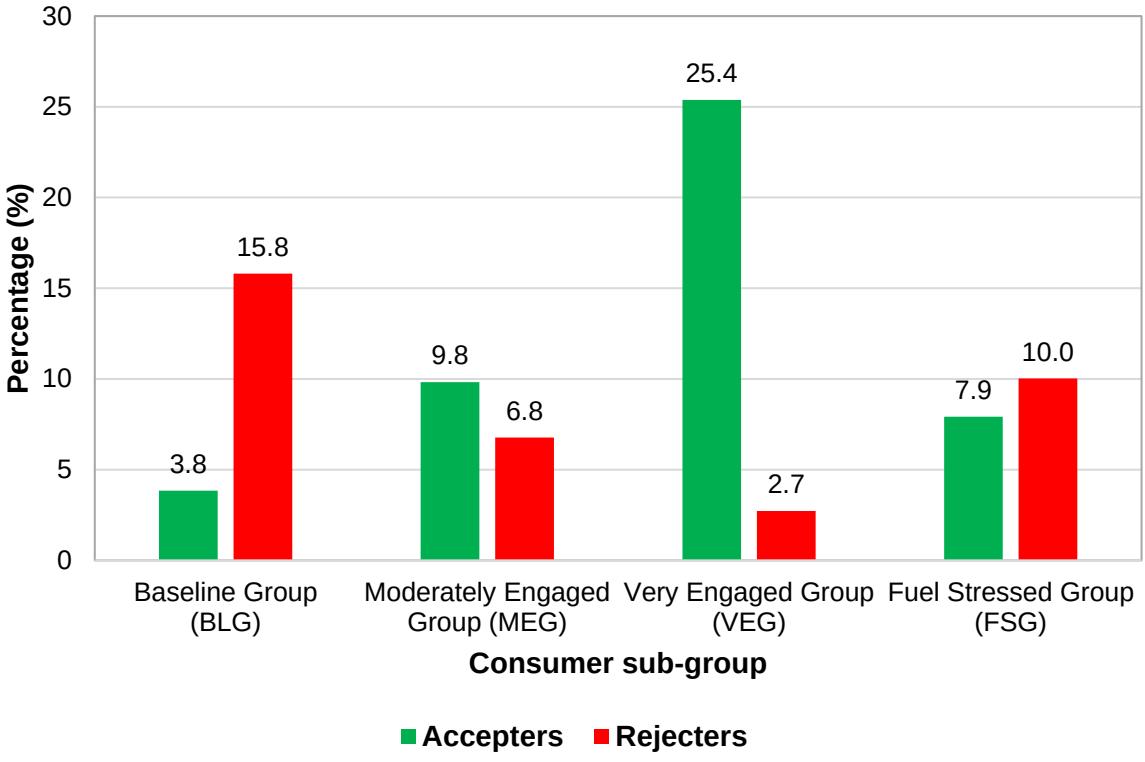


Fig. 0-4. Breakdown of hydrogen acceptance and rejection by consumer sub-group relative to sample size.

Measurement model assessment

In the case of the BLG, all indicator loadings met the threshold value of 0.708, while one indicator loading failed to satisfy this threshold for the MEG (PP1 = 0.409). Regarding the VEG, three indicators fell marginally below the CA threshold: BLR2 = 0.682; FIN2 = 0.693; ADPT = 0.671. Additionally, and concurring with the result for the MEG, PP1 had a CA value of 0.578. Finally, the FSG reflected a similar pattern, reporting a value of 0.445 for PP1, in addition to 0.668 for PP5, while three other indicators failed to satisfy the recommended threshold: BL3 = 0.596; FP1 = 0.550; FP2 = 0.532. Table 0-6–Table 0-14 report the measurement model assessment for the remaining sub-groups, following the report for the BLG in the main analysis.

Table 0-6. Assessment of reliability, convergent validity, and multicollinearity for the Moderately Technology and Environmentally Engaged Group.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety Perceptions (SP)	0.924	0.925	0.943	0.768	1.224
Boiler Attributes (BLR)*	0.765	0.768	0.850	0.588	1.657
Hob Attributes (HOB)*	0.861	0.864	0.906	0.706	1.657
Technology Perceptions (TP)**	0.773	0.773	0.898	0.815	1.149
Financial Perceptions (FP)	0.740	0.933	0.812	0.593	1.053
Perceived Socio-economic Costs (PSC)	0.678	0.686	0.861	0.756	1.200
Production Perceptions (PP)	0.762	0.808	0.836	0.516	1.253
Hydrogen Adoption (ADPT)	0.832	0.842	0.870	0.528	n/a

** Higher-order construct
* Lower order constructs

Table 0-7. Fornell Larcker results for the Moderately Technology and Environmentally Engaged Group.

	BLR	FP	HOB	ADPT	PC	PP	SP
BLR	0.767						
FP	-0.160	0.770					
HOB	0.630	-0.078	0.840				
ADPT	0.382	-0.269	0.376	0.727			
PSC	-0.113	0.164	-0.133	-0.465	0.869		
PP	0.138	-0.095	0.160	0.494	-0.382	0.719	
SP	0.270	-0.162	0.341	0.526	-0.159	0.290	0.876

Table 0-8. HTMT results for the Moderately Technology and Environmentally Engaged Group.

	BLR	FP	HOB	ADPT	PSC	PP	SP
BLR							
FP	0.182						
HOB	0.773	0.107					
ADPT	0.412	0.270	0.373				
PSC	0.181	0.180	0.169	0.609			
PP	0.214	0.106	0.206	0.560	0.498		
SP	0.320	0.160	0.382	0.551	0.194	0.372	

Table 0-9. Assessment of reliability, convergent validity, and multicollinearity for the Very Technology and Environmentally Engaged Group.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety Perceptions (SP)	0.929	0.931	0.946	0.779	1.568
Boiler Attributes (BLR)*	0.735	0.739	0.834	0.558	1.843
Hob Attributes (HOB)*	0.865	0.865	0.908	0.712	1.843
Technology Perceptions (TP)**	0.803	0.804	0.911	0.836	1.417
Financial Perceptions (FP)	0.684	0.798	0.796	0.567	1.054
Perceived Socio-economic Costs (PSC)	0.785	0.833	0.901	0.820	1.063
Production Perceptions (PP)	0.754	0.765	0.834	0.504	1.253
Domestic Hydrogen Adoption Potential (ADPT)	0.830	0.838	0.873	0.534	n/a

** Higher-order construct
* Lower order constructs

Table 0-10. Fornell Larcker results for the Very Technology and Environmentally Engaged Group.

	BLR	FP	HOB	ADPT	PC	PP	SP
BLR	0.747						
FP	-0.109	0.753					
HOB	0.676	-0.096	0.844				
ADPT	0.417	-0.230	0.471	0.731			
PSC	-0.062	0.059	-0.060	-0.205	0.906		
PP	0.243	-0.165	0.304	0.591	-0.177	0.710	
SP	0.411	-0.199	0.537	0.573	-0.055	0.384	0.883

Table 0-11. HTMT results for the Very Technology and Environmentally Engaged Group.

	BLR	FP	HOB	ADPT	PSC	PP	SP
BLR							
FP	0.205						
HOB	0.846	0.134					
ADPT	0.497	0.257	0.500				
PSC	0.214	0.281	0.102	0.250			
PP	0.333	0.265	0.378	0.735	0.277		
SP	0.495	0.234	0.598	0.611	0.064	0.475	

Table 0-12. Assessment of reliability, convergent validity, and multicollinearity for the Fuel Stressed Group.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety Perceptions (SP)	0.892	0.894	0.921	0.699	1.224
Boiler Attributes (BLR)*	0.673	0.685	0.803	0.508	1.657
Hob Attributes (HOB)*	0.836	0.837	0.891	0.671	1.657
Technology Perceptions (TP)**	0.744	0.744	0.886	0.796	1.149
Financial Perceptions (FP)	0.703	0.717	0.733	0.498	1.053
Perceived Socio-economic Costs (PSC)	0.749	0.758	0.888	0.799	1.200
Production Perceptions (PP)	0.772	0.825	0.842	0.527	1.253
Hydrogen Adoption (ADPT)	0.836	0.843	0.877	0.543	n/a

** Higher-order construct
* Lower order constructs

Table 0-13. Fornell Larcker results for the Fuel Stressed Group.

	BLR	FP	HOB	ADPT	PC	PP	SP
BLR	0.713						
FP	-0.170	0.706					
HOB	0.592	-0.127	0.819				
ADPT	0.422	-0.295	0.425	0.737			
PSC	-0.267	0.297	-0.253	-0.402	0.894		
PP	0.248	-0.116	0.256	0.472	-0.262	0.726	
SP	0.369	-0.154	0.394	0.499	-0.153	0.301	0.836

Table 0-14. HTMT results for the Fuel Stressed Group.

	BLR	FP	HOB	ADPT	PSC	PP	SP
BLR							
FP	0.296						
HOB	0.784	0.169					
ADPT	0.541	0.270	0.469				
PSC	0.363	0.230	0.319	0.493			
PP	0.344	0.161	0.324	0.545	0.327		
SP	0.486	0.168	0.457	0.558	0.190	0.365	

Measurement model assessment for higher-order construct

Fig. 0-5 presents the PLS-SEM output for validating the higher-order construct, Technology Perceptions (TP) across the full sample, following the guidelines presented by Becker et al. [62]. The disjoint two-stage approach was applied whereby the latent variable scores for each lower-order construct (Boiler Performance and Hob Performance) are calculated and used as indicators for the newly formed first-order construct, Technology Perceptions (TP). As shown in Table 5-8, (for the BLG), this procedure validated the average variance extracted (AVE) in support of convergent validity, while discriminant validity was also established, alongside item reliability and internal consistent reliability.

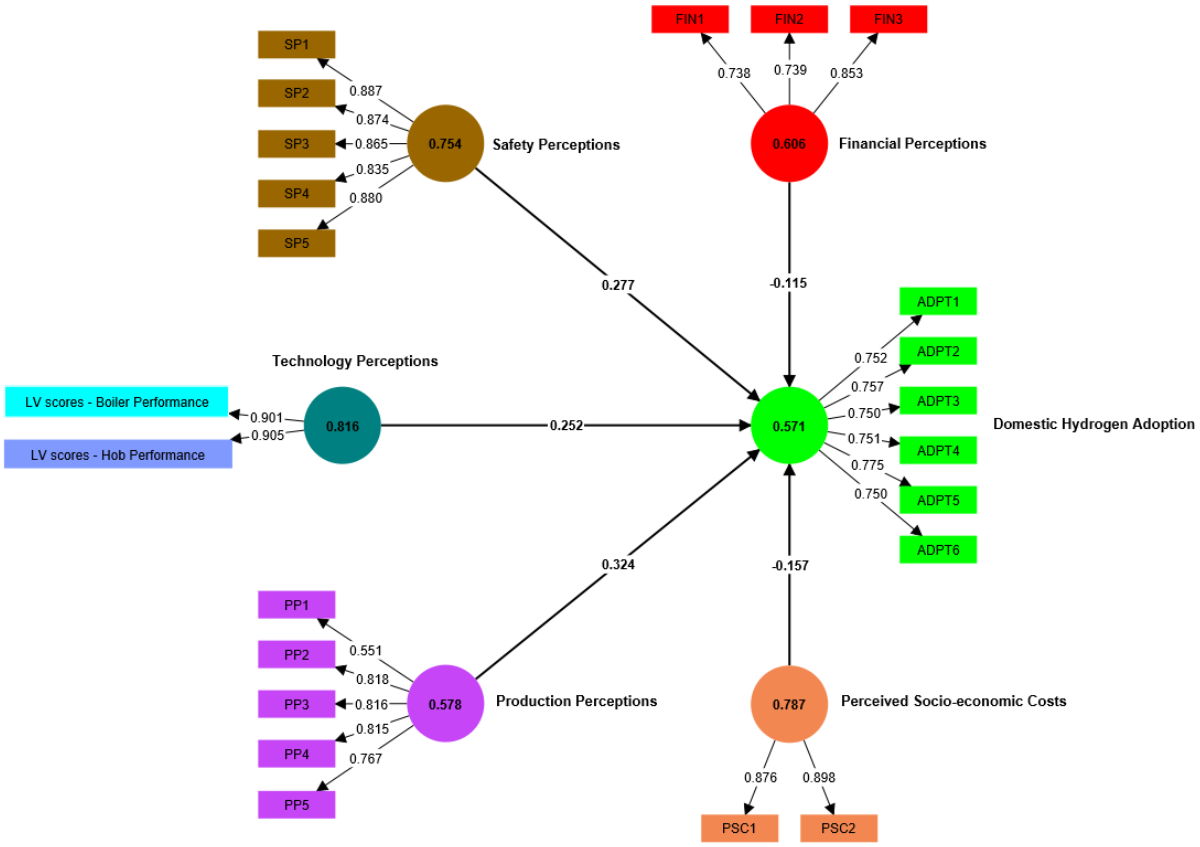


Fig. 0-5. Measurement model assessment for reflective-formative construct (TP).

Structural model assessment

Fig. 0-6–Fig. 0-9 report the structural model path coefficients for each consumer sub-group.

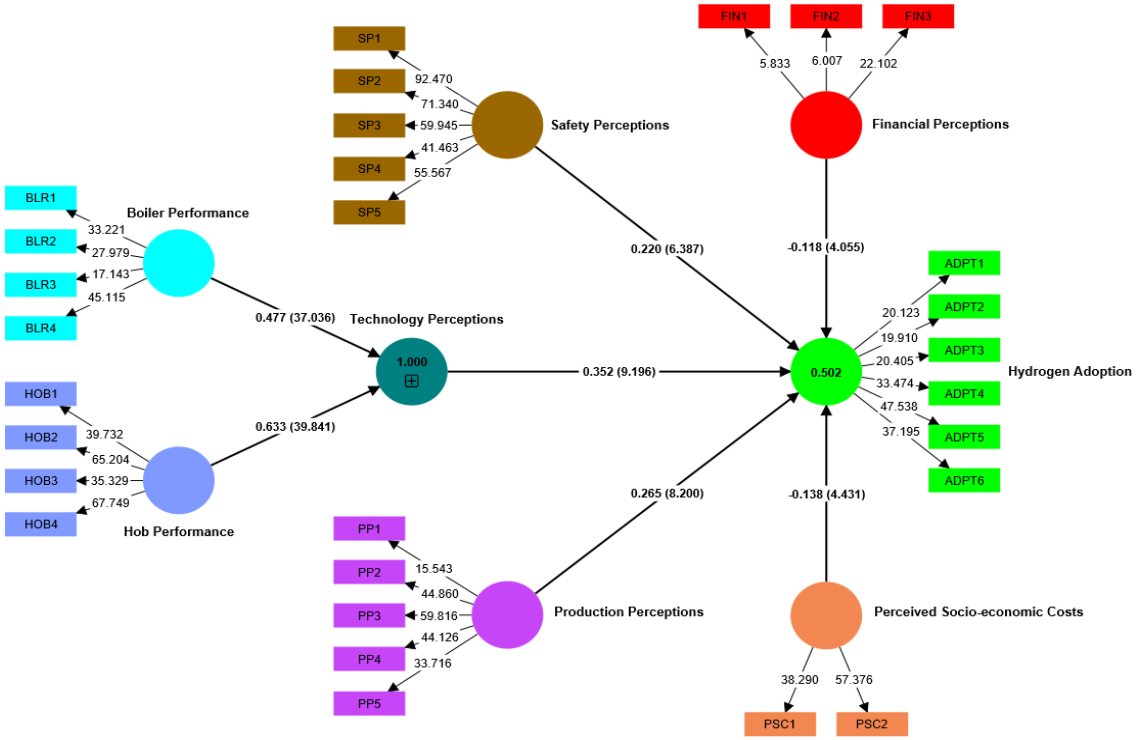


Fig. 0-6. Structural model path coefficients for Baseline Group.

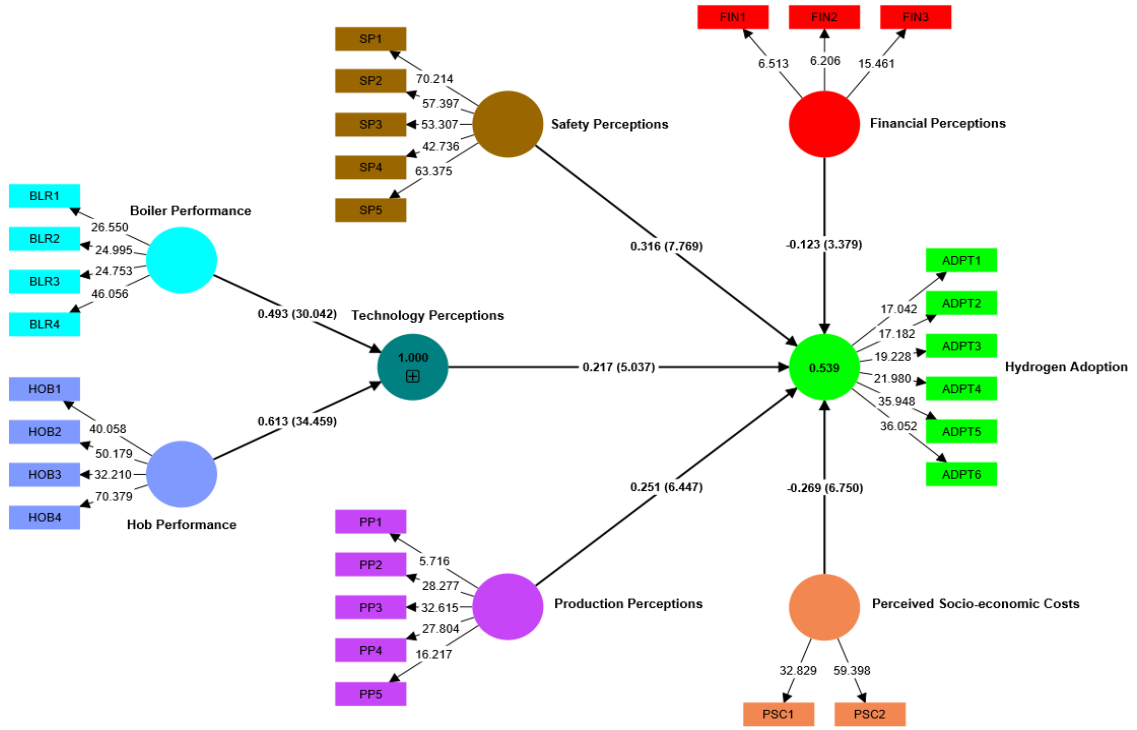


Fig. 0-7. Structural model path coefficients for Moderately technology and environmentally Engaged Group.

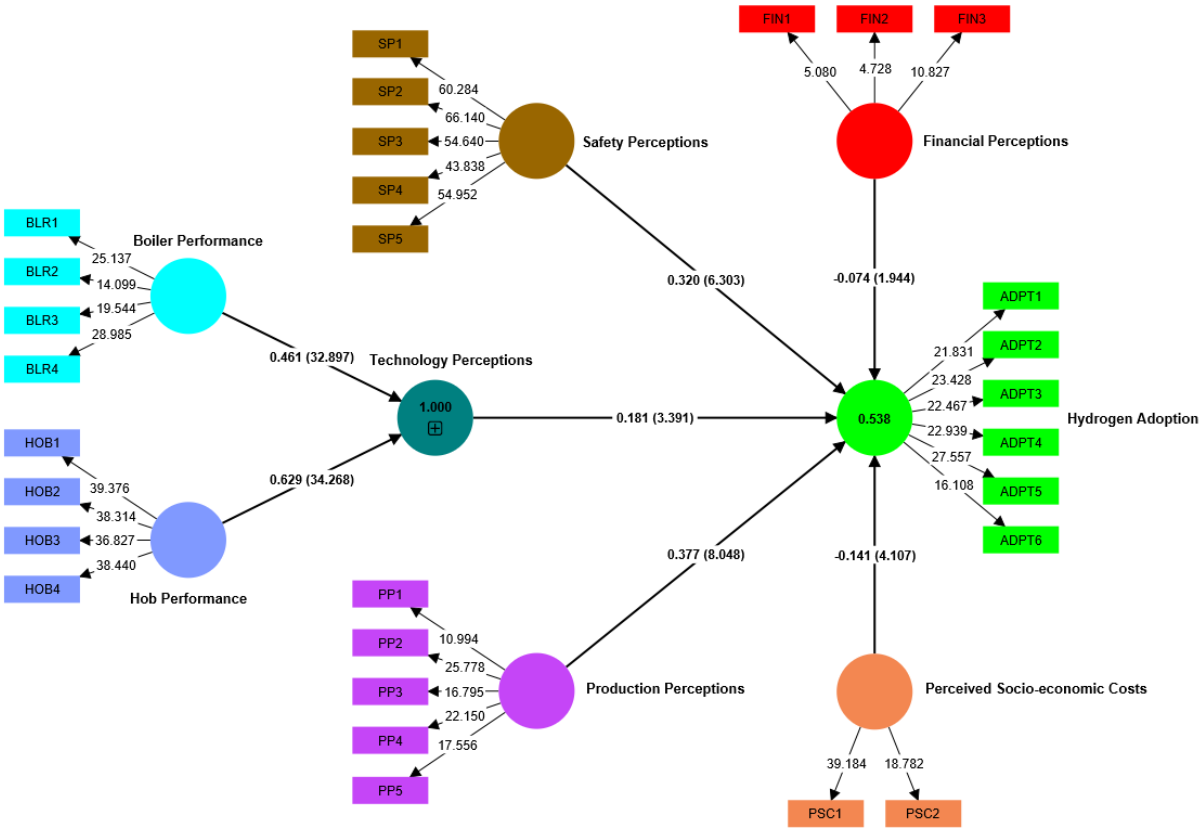


Fig. 0-8. Structural model path coefficients for Very technology and environmentally Engaged Group.

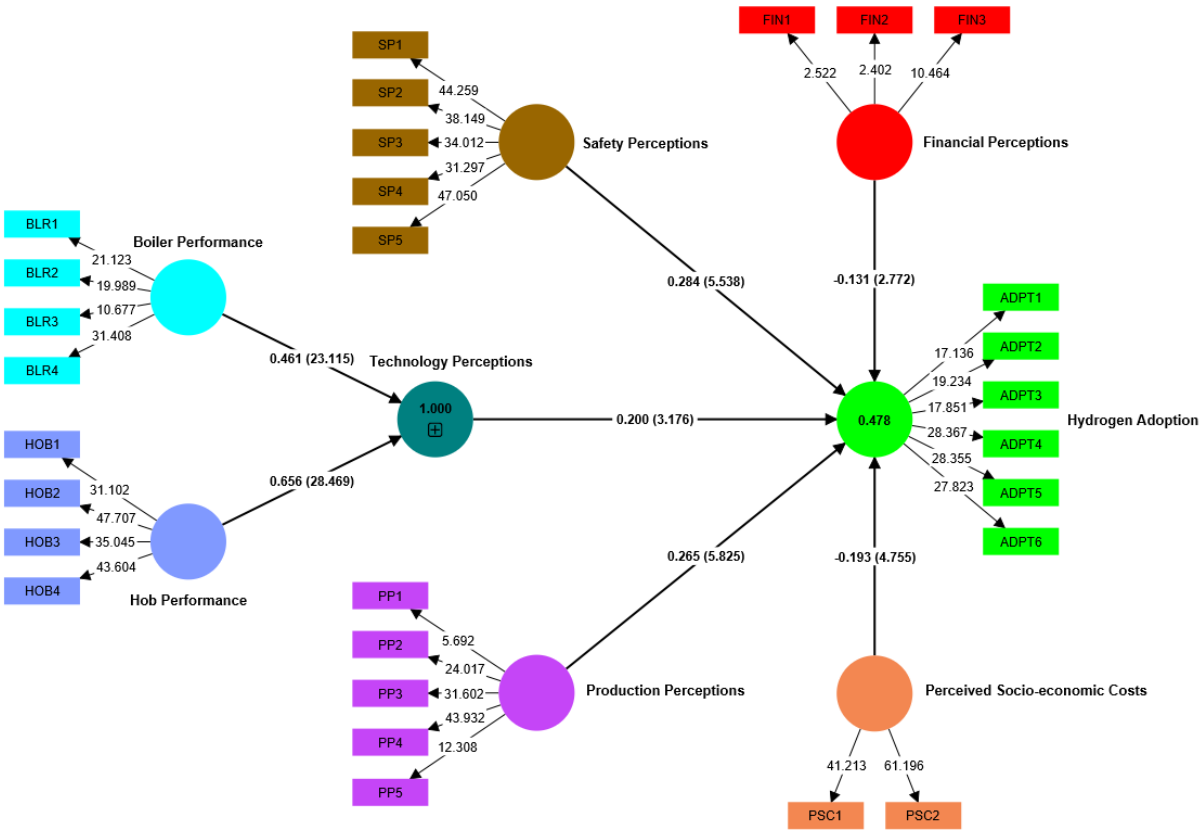


Fig. 0-9. Structural model path coefficients for Fuel Stressed Group.

Cross-validated predictive ability test

Table 0-15 reports the results for the CVPAT, which confirms moderative out-of-sample predictive power for the model across each consumer sub-group.

Table 0-15. Results for predictive power using CVPAT.

Baseline Group		***PLS-SEM vs Indicator average (IA)***		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	-0.852	10.344	<0.001
	Technology Perceptions (TP)	-2.865	14.136	<0.001
	Overall	-2.002	14.678	<0.001
		PLS-SEM vs Linear model (LM)		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	0.035	1.475	0.141
	Technology Perceptions (TP)	3.080	29.333	<0.001
	Overall	1.775	29.043	<0.001
Moderately Engaged Group		***PLS-SEM vs Indicator average (IA)***		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	-0.785	9.234	<0.001
	Technology Perceptions (TP)	-3.047	12.070	<0.001
	Overall	-2.007	13.131	<0.001
		PLS-SEM vs Linear model (LM)		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	0.016	0.519	0.604
	Technology Perceptions (TP)	2.773	23.779	<0.001
	Overall	1.591	24.472	<0.001
Very Engaged Group		***PLS-SEM vs Indicator average (IA)***		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	-0.754	6.973	<0.001
	Technology Perceptions (TP)	-3.118	9.566	<0.001
	Overall	-2.105	9.984	<0.001
		PLS-SEM vs Linear model (LM)		
		Average loss difference	***t*-value**	***ρ*-value**

	Hydrogen Adoption (ADPT)	0.026	0.501	0.617
	Technology Perceptions (TP)	2.749	18.925	<0.001
	Overall	1.582	18.456	<0.001
Fuel Stressed Group		***PLS-SEM vs Indicator average (IA)***		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	-0.852	10.344	<0.001
	Technology Perceptions (TP)	-2.865	14.136	<0.001
	Overall	-2.002	14.678	<0.001
		PLS-SEM vs Linear model (LM)		
		Average loss difference	***t*-value**	***ρ*-value**
	Hydrogen Adoption (ADPT)	0.035	1.475	0.141
	Technology Perceptions (TP)	3.080	29.333	<0.001
	Overall	1.775	29.043	<0.001

Importance-performance map analysis

Table 0-16 reports the results for the importance-performance map analysis conducted at the construct level for the full sample, as well as each sub-group (see Section 5.6.5).

Table 0-16. Total effects and latent variable index values for predictors of domestic hydrogen adoption potential.

		Adoption construct						
Consumer sub-group	**IMPA measurement**	**BLR**	**HOB**	**TP**	**FP**	**PSC**	**SP**	**PP**
Baseline Group (BLG)	Importance (total effects)	0.168	0.223	0.352	-0.118	-0.138	0.220	0.265
	Performance (LV index values)	68.387	59.426	63.503	64.843	48.056	55.612	59.417
Moderately Engaged Group (MEG)	Importance (total effects)	0.107	0.133	0.217	-0.123	-0.269	0.316	0.251
	Performance (LV index values)	70.113	62.318	66.039	63.206	44.189	58.745	67.131
Very Engaged Group (VEG)	Importance (total effects)	0.083	0.114	0.181	-0.074	-0.141	0.320	0.377
	Performance (LV index values)	75.718	68.281	71.659	62.589	45.081	66.027	73.558
Fuel Stressed Group (FSG)	Importance (total effects)	0.092	0.131	0.200	-0.131	-0.193	0.284	0.265
	Performance (LV index values)	71.404	61.403	65.634	57.759	49.664	57.611	60.395

Fig. 0-10–Fig. 0-13 report the importance-performance map analyses for each consumer sub-group.

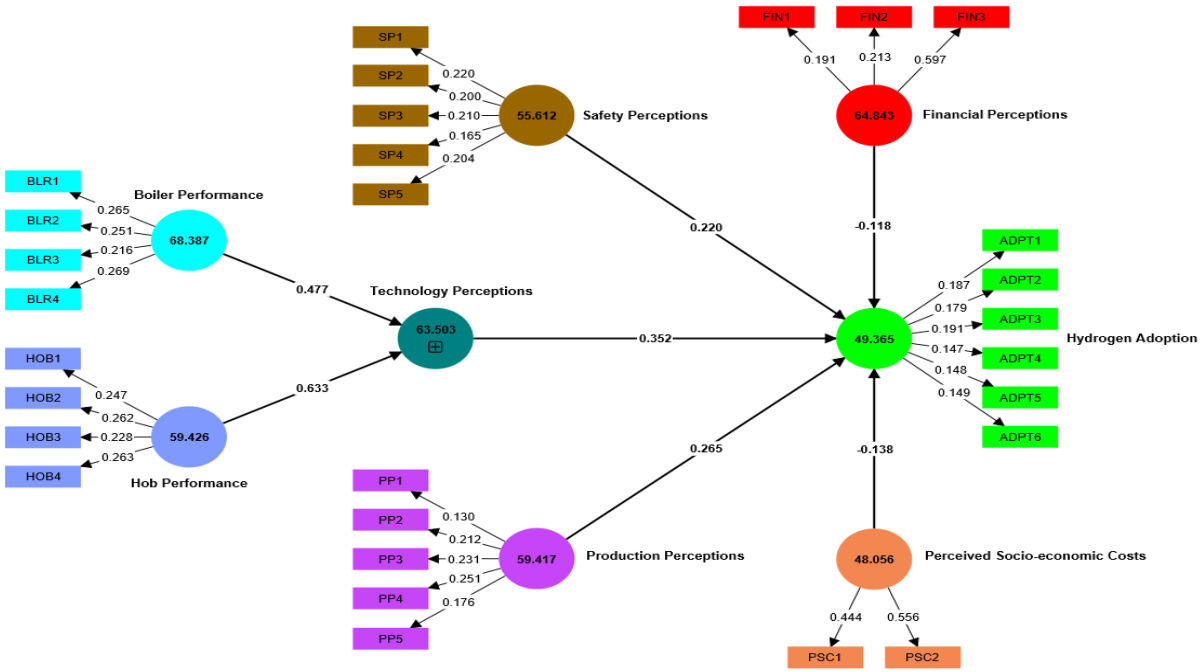


Fig. 0-10. Importance-performance map analysis for Baseline Group.

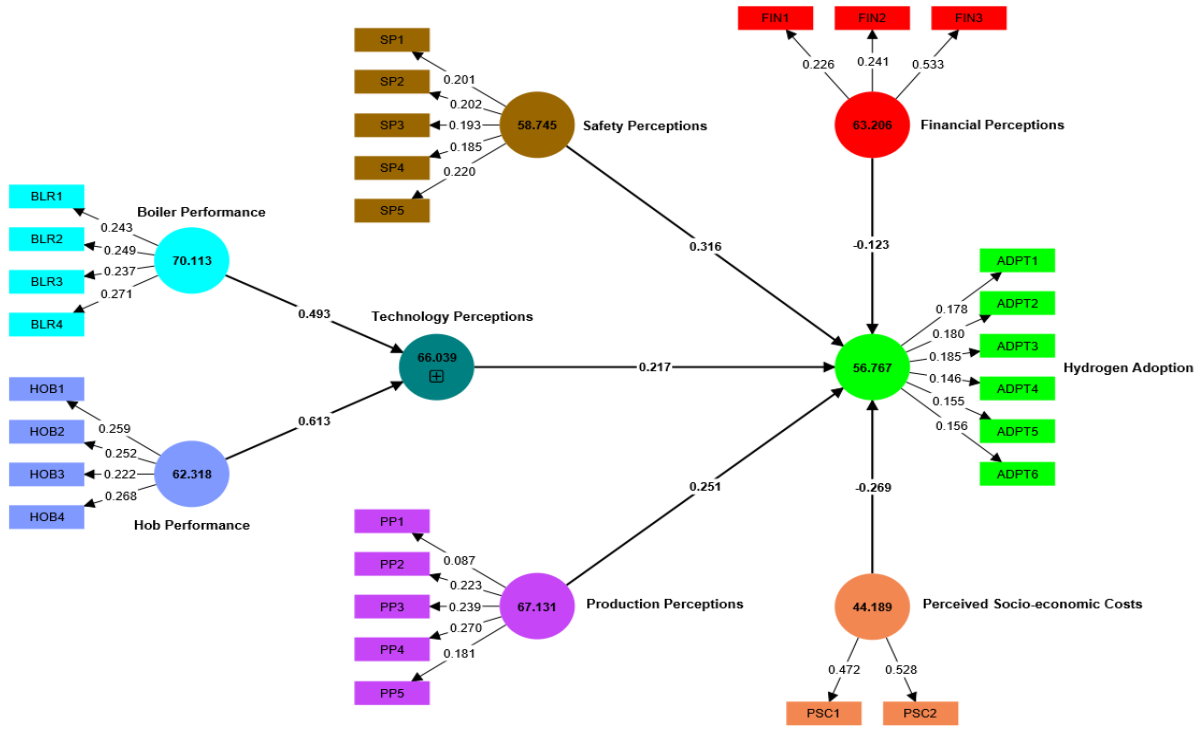


Figure 0-11. Importance-performance map analysis for Moderately technology and environmentally Engaged Group.

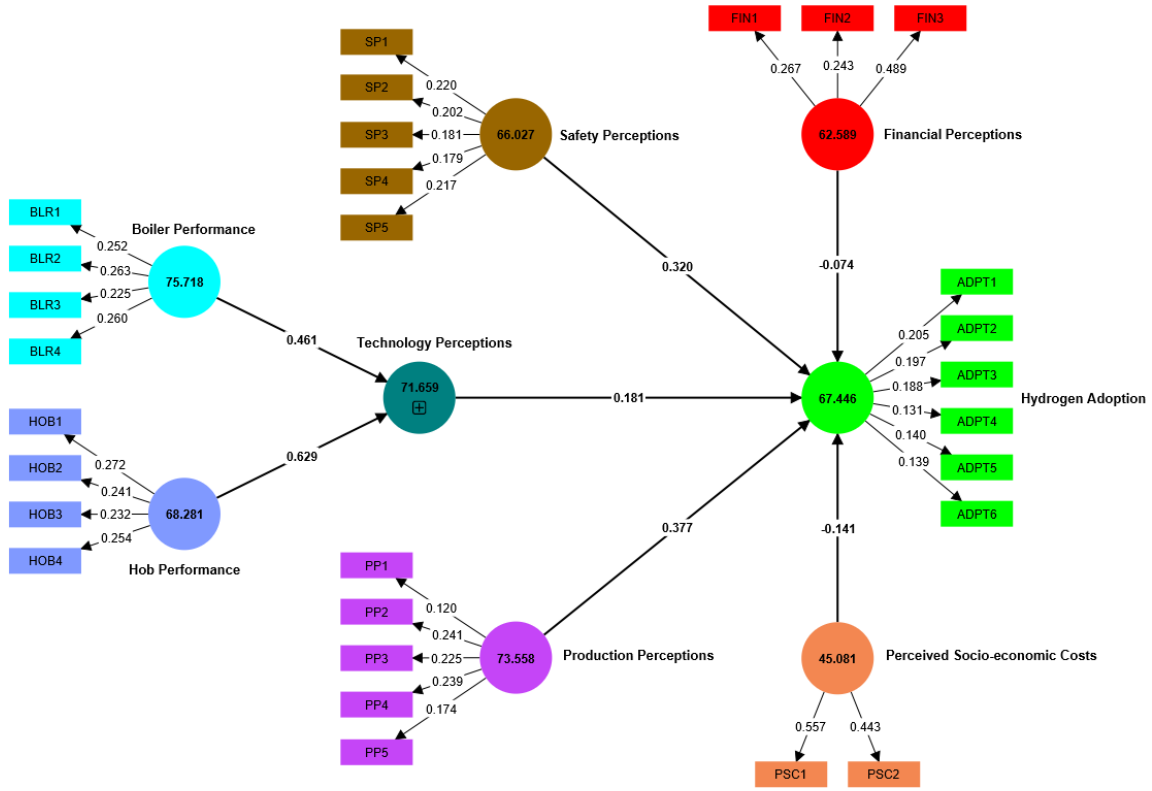


Fig. 0-12. Importance-performance map analysis for Very technology and environmentally Engaged Group.

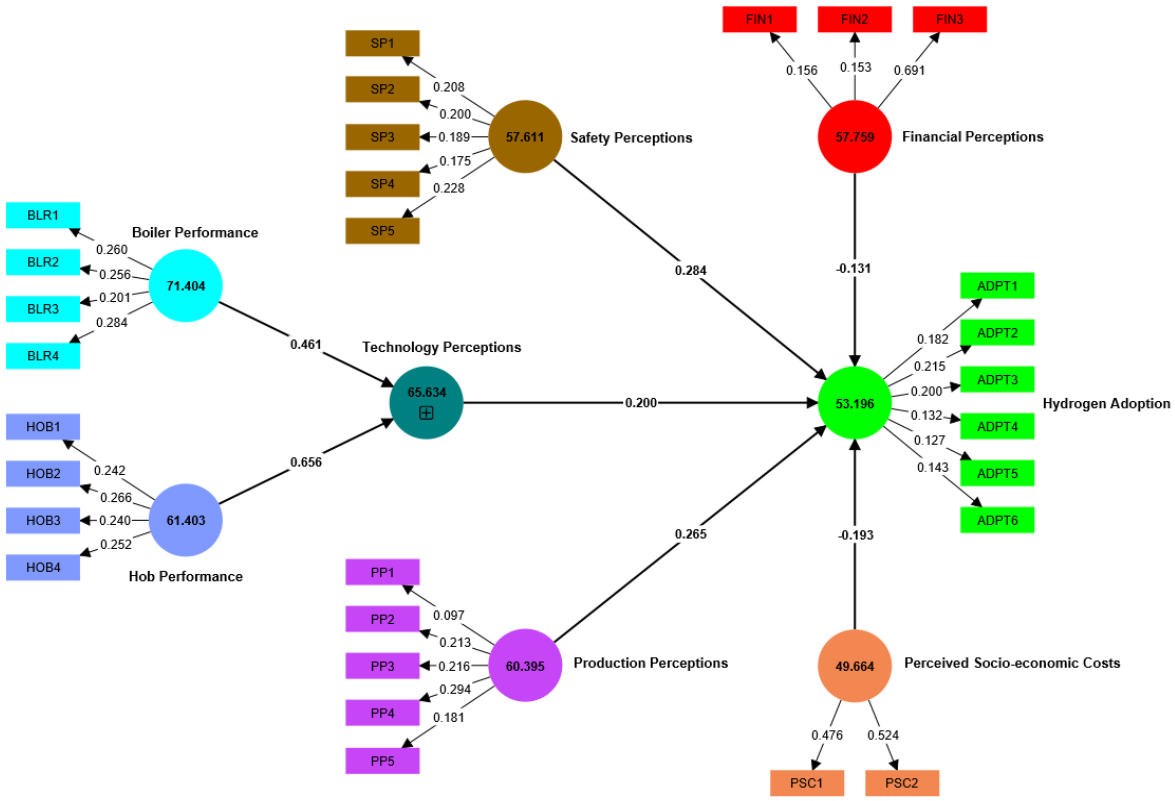


Fig. 0-13. Importance-performance map analysis for Very technology and environmentally Engaged Group.

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APPENDIX P. General discussion

Fig. P-1–Fig. P-4 reports the results from the analysis of qualitative responses to the online survey which presented a specific consumer perspective towards domestic hydrogen (N = 1213), as captured in Appendix G. The results corroborate the positions supported by respective consumer sub-groups within the PLS-SEM phase of the research (i.e. PLS-MGA), as well as Chapter 3.

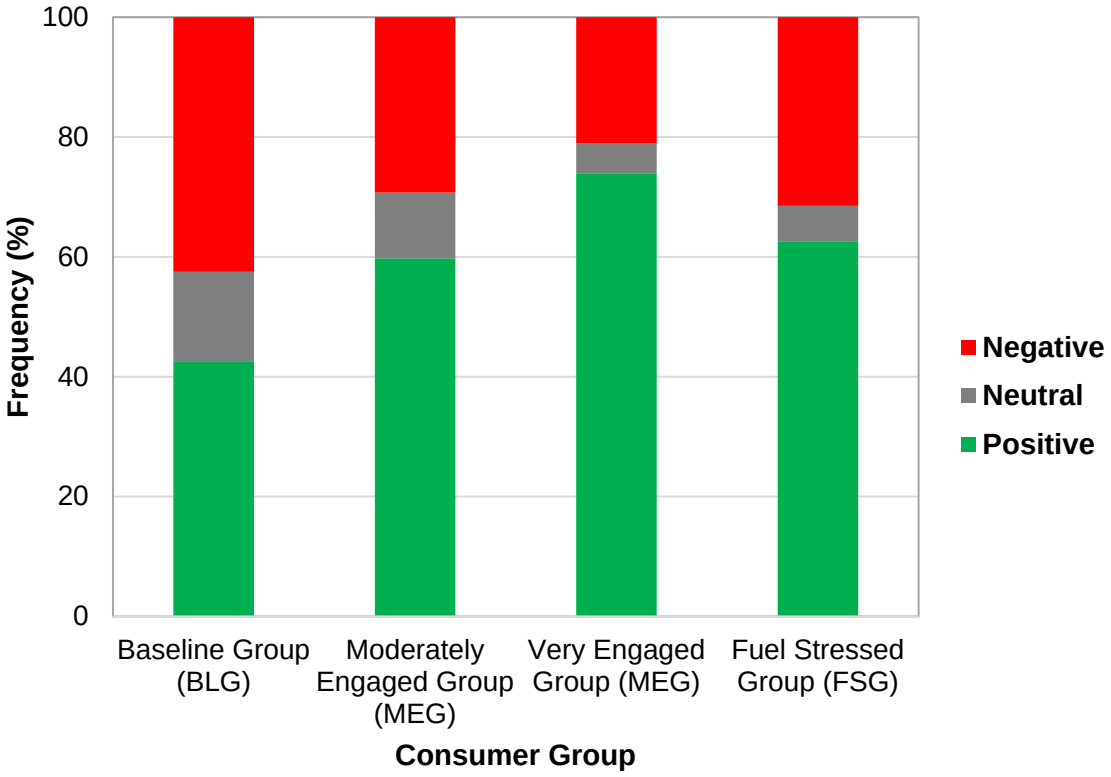

Fig. P-1. Distribution of positive, negative and neutral perspectives of domestic hydrogen across consumer sub-groups.

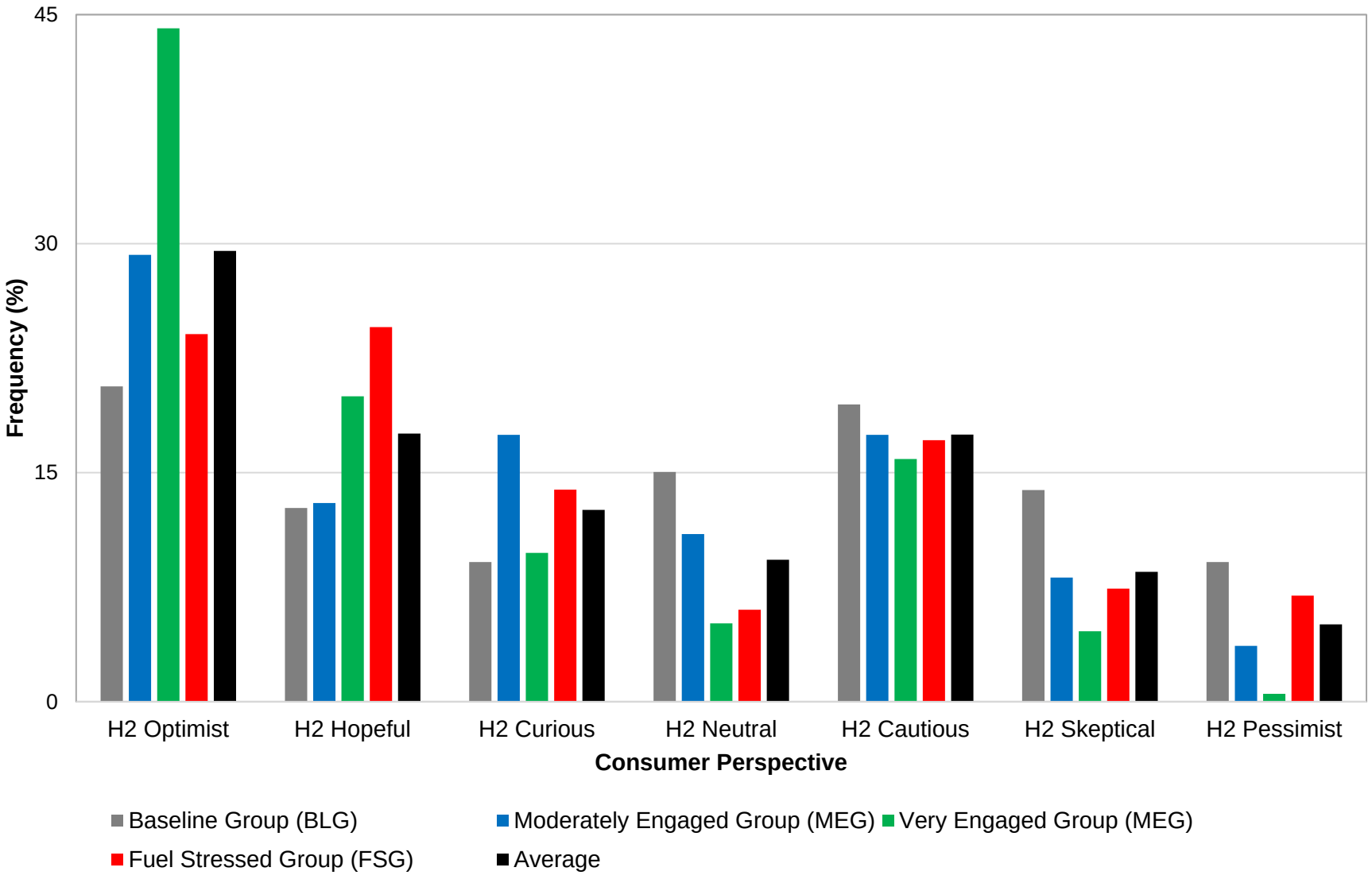

Fig. P-2. Distribution of one-dimensional perspectives of domestic hydrogen across consumer sub-groups.

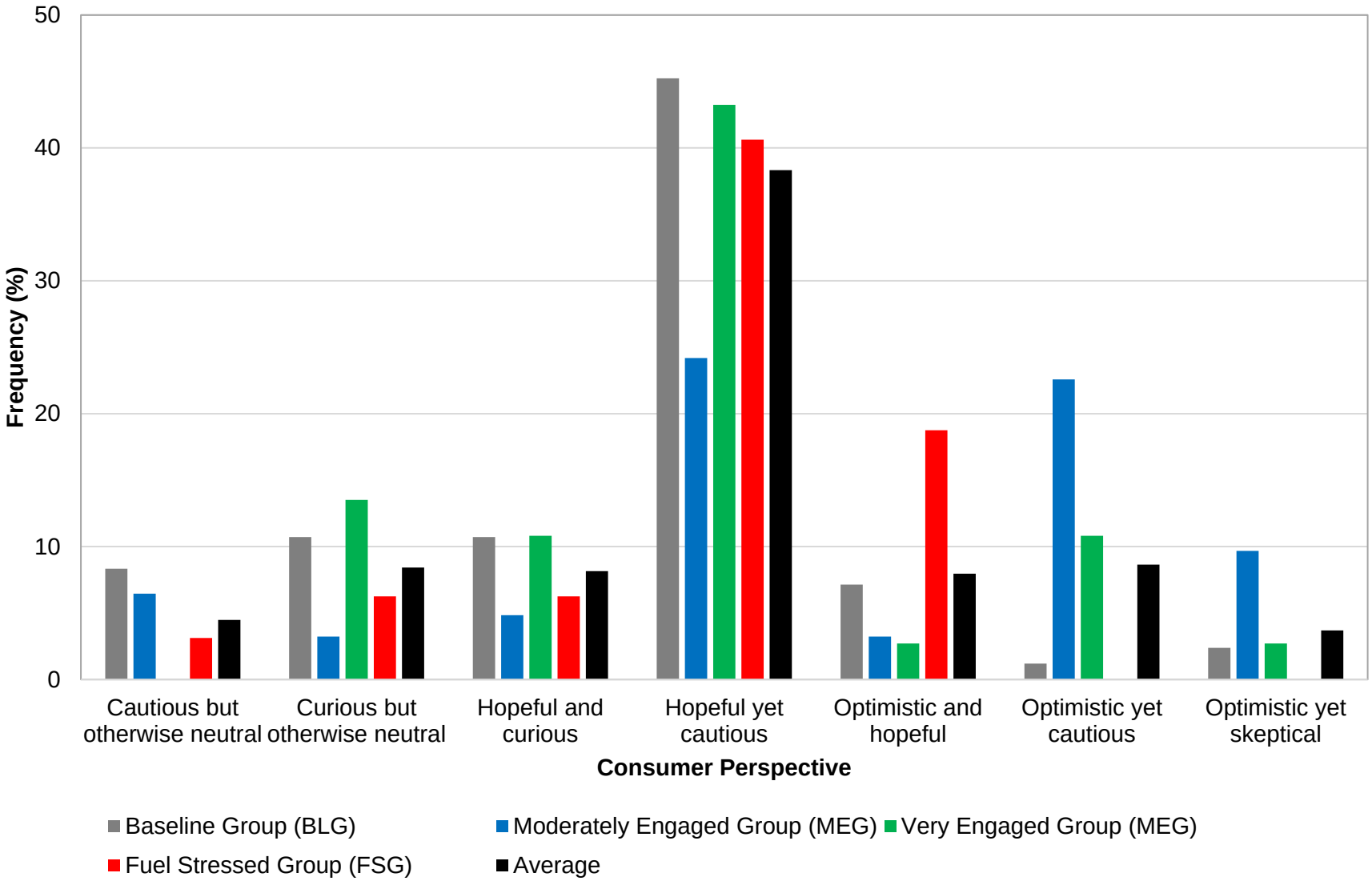

Fig. P-3. Distribution of two-dimensional perspectives of domestic hydrogen across consumer sub-groups.

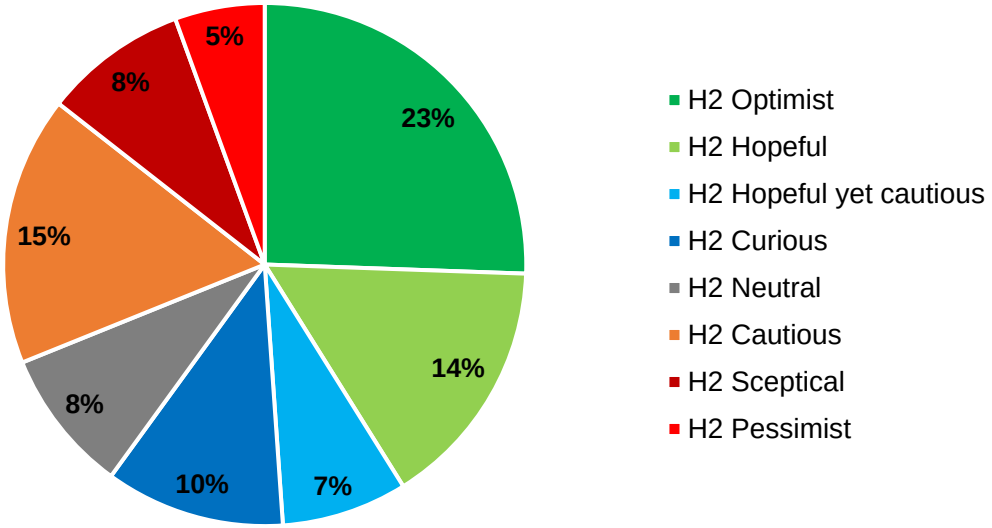

Fig. P-4. Consumer perspectives towards domestic hydrogen across sample.

APPENDIX Q. General conclusions and recommendations

Challenges in the recruitment stage and emergent response

Online focus groups were conducted between February and April 2022 to support the exploratory, qualitative phase of the research (see Appendix D–F). However, some challenges were encountered during the recruitment phase, which inhibited the original plan to conduct 7 focus groups with 6 to 8 participants in each case (N = ~45).

The first focus group – a pilot test with participants from Marston Moretaine, Bedford – was conducted as planned (N = 5) since less participants were acceptable for the purpose of validating the topic guide and research design. Foremost, this group represented citizens with a moderate level of renewable energy engagement, which provided a comparative lens when interacting with very engaged citizens from the same jurisdiction in the subsequent session (N = 6). Additionally, the results from the pilot group were valid for inclusion in the main analysis, which was factored into plans when consolidating the final sample size.

However, the next stage of the research (Focus Groups 3–7) was characterised by degrees of unpredictability and uncertainty, following higher than expected drop-out rates, which were partially attributed to cases of COVID-19 and other unforeseen events such as last-minute recruitment challenges. As a result, Focus Group 3 (owners of solar PV panels and smart devices), Focus Group 4 (environmentally engaged citizens), and Focus Group 6 (fuel poor/stressed respondents) were limited to three participants in each case (see **Error! Reference source not found.**). A dditionally, Focus Group 5 (citizens living in an industrial town or city) was partially underrepresented (N = 5), whereas the Baseline Group (FG7) met the lower threshold (N = 6). As a result, the sample was restricted to 31 participants upon completion of FG7, which was unsatisfactory for the intended research design.

In the process of analysing the available dataset and enacting a contingency plan, it emerged that successful recruitment of fuel stressed respondents was more feasible when targeting urban and industrial locations. In turn, this filtering approach offset the need for further direct engagement with non-fuel stressed participants from industrial towns, leading to a high turnout in the final focus group (FG10: N = 10). Similarly, it was apparent that owners of solar PV panels and smart meters were by default at

least moderately engaged in renewable energy, which guided the decision to target this group directly (FG9: N = 8). Finally, to compensate for under-representation in FG4, a subsequent round of environmentally engaged citizens was also recruited (FG8: N = 9). The follow-up focus groups were carried out between April 4–6 to support Phase 2 of the project, leading to a more acceptable sample size (N = 58). As reflected, a more liberal recruitment approach was taken to meet sample size requirements.

In view of these developments, the focus groups dataset analysed within PhD thesis is subject to some unique dynamics, whereby FG3, FG4, and FG6 presented an extremely tight-knit discussion between participants, whereas FG8–FG10 presented a looser, interactive environment which also saw the emergence of more vocal participants at times. Overall, this combination provided a useful balance to support the exploratory nature of the research, while the emergent design also resulted in a larger sample size, which supported comparative insights and more robust analysis of poll results. Nevertheless, these dynamics should be noted and pre-empted in future research efforts, which can be achieved by targeting a range of 7–9 participants to offset the risk of under-representation. At the same time, researchers may choose to deliberately target smaller group sizes for deeper engagement levels, but should employ this approach in a premeditated way, rather than through an emergent, dynamic response to quota constraints.

Challenges in coding responses and emergent response

Chapter 3 and Appendix G reflect the challenge of codifying a large qualitative dataset. While a total of 1213 responses were given to the open-ended question at the end of the online survey, not all responses corresponded directly to identifying a specific sub-factor of domestic hydrogen acceptance. As reported in Chapter 3, 1064 responses made an explicit reference to at least one factor of domestic hydrogen acceptance, whether positive, neutral, or negative. This discrepancy (-12.3%) highlights the iterative and reflexive nature of thematic analysis and associated qualitative methods [1], which generate knowledge sourced from human experience [2]. In facilitating theoretical openness, thematic analysis supports research flexibility in data handling to meet the intended goals of the study [3]. However, through this constructivist research paradigm [4], researchers must overcome risks of inconsistency and incoherence when undertaking thematic analysis [5].

In this study, these risks or limitations were largely overcome by strictly adhering to best research practices for precision, consistency, systematisation, and transparency [1,6], which included implementing the highest level of scrutiny when analysing data patterns and evaluating emergent codes/themes (i.e. 'core factors', 'subfactors' and 'consumer perspectives').[1] Consequently, the twin outputs delivered in the final research stage (i.e. Stage 2 of Phase 3) fulfilled the requirements of credibility, transferability, dependability, confirmability, clear audit trails, and reflexivity [1]. Nevertheless, the inherent nature of the approach sees the researcher become "the instrument for analysis," tasked with the responsibility of judging the codes and themes, and decontextualising and recontextualising the data [1].

The principal limitation lies with the subjective nature of the thematic approach, which means final decisions around categorisation may remain 'fuzzy' in specific instances or remain open to subsequent iteration(s) in follow-up research. For example, when mapping participant statements around the 'cost-of-living crisis', it emerged that many comments presented a neutral framing, whereby the response was contingent as opposed to negative (i.e. as suggested by the theme itself). Such intricacies present difficulties in deriving clear-cut data patterns, when compared to clearly polarised sub-themes (i.e. sub-factors) such as safety benefits and safety costs, as presented in Chapter 13. The nature of subjective coding has a direct knock-on effect to correctly estimating the balance between optimistic and pessimistic responses via the associated latent factor approach, as performed in Chapter 14. While these trade-offs are inherent to qualitative research practices, internalising the significance of such observations can help guide future studies.

Challenges in the piloting stage and emergent response

The research design implemented for the online survey was subject to certain constraints, which called for an adaptive sampling strategy. The original ambition was to target five groups: technology engaged consumers (non-fuel poor); environmentally

[1] The measures included the following: several weeks of familiarisation with the dataset; initial generation of codes and searching for themes following word-by-word decomposition of every statement in the dataset; comprehensive revising of emergent themes and cross-checks for consistency across the dataset (i.e. at the sub-group level); careful mapping and defining of themes to establish 12 'core' factors of domestic hydrogen acceptance and 48 corresponding sub-factors, in addition to seven one-dimensional acceptance positions and 19 multi-dimensional perspectives; and validation of thematic results through descriptive and statistical analysis, which supported a final stage of iteration.

engaged consumers (non-fuel poor); technology and environmentally engaged consumers (non-fuel poor); fuel poor respondents (non-technology and environmentally engaged); and a ‘baseline’ group (non-technology and environmentally engaged, and non-fuel poor). Within this design, the baseline group (BLG) was targeted to be double the size (i.e. N = 800) of the remaining smaller sub-groups (i.e. each N = 400), which was broadly implemented in the modified sampling approach.

The additional novelty of the suggested approach was to directly capture differences between technology and environmental engagement, while also exploring the combined effect of corresponding levels of high engagement. The inclusion of five sub-groups would afford opportunities for a maximum of ten pairwise comparisons within PLS-MGA, or non-parametric tests (i.e. K-W test). However, piloting of the online survey throughout September 2022 demonstrated the difficulty of securing sufficient sample sizes for the technology engaged and environmentally engaged groups. At this juncture, it should also be noted that a strictly ‘fuel poor’ group could not be secured. Instead, the filtering approach was relaxed to target citizens expressing high levels of ‘fuel stress’.

Following careful deliberation and further piloting to assess feasibility, the decision was taken to retain the Very technology and environmentally Engaged group (VEG), while dissolving the individual engaged groups. Instead, a Moderately technology and environmentally Engaged group (MEG) was recruited for comparative purposes and in view of practicalities. Accordingly, six pairwise comparisons were available through the final research approach. This compromise or adjustment proved highly satisfactory for supporting the final stage of the research, which included implementing PLS-MGA (see Chapter 5), while exploring the emerging contours of consumer heterogeneity in relation to domestic hydrogen acceptance (see Chapter 3 and Appendix G). Nevertheless, it became somewhat indeterminate whether technology engagement and environmental attitude have distinct effects on respective acceptance and adoption constructs, in addition to overall acceptance and adoption potential for hydrogen homes.[2]

[2] The analysis undertaken in Appendix G partially overcame this constraint by constructing separate hypotheses for each aspect of technology and environmental engagement, and testing the effects on both domestic hydrogen adoption and acceptance.

One approach to potentially overcome this drawback is to extract new groups based on responses to filtering questions (i.e. self-rated knowledge and awareness about renewable energy technologies, self-perceived adoption category, and self-assessed interest and engagement level with environmental issues), which would approximate a form of artificial dichotomisation via data filtering techniques [7]. While such a data transformation technique would be grounded in a strong underlying rationale [7], the approach is not in line with best research practices and may introduce downward bias in estimated path coefficients and pairwise comparisons, while reducing statistical power [8]. Additionally, employing artificial dichotomisation may fail to secure sufficient sample sizes for subsequent analyses via PLS-SEM [9].

Acknowledging sample size constraints is critical, as reflected in the process of this research. Although 2100 responses were recorded for initial analysis (including valid pilot responses), around 12% of the preliminary sample was removed due to missing data, straight-lining, or other inconsistencies (N = 1845). Consequently, the VEG was partially underrepresented (N = 331), given that this sub-group proved the hardest to reach. In response, researchers should adhere to avoiding artificial dichotomisation by ensuring that desired consumer segments are directly secured, while also aiming to secure a large sample size for each group. Furthermore, sample sizes should be relatively equal to help maximise statistical power [10,11].

In this study, the larger size of the BLG (N = 677) did not present a limitation to the research design, since various tests were undertaken to compare a reduced sample (i.e. 400) against the other groups, which had no significant effect on statistical results. Accordingly, the decision to retain the full BLG sample was justified. Furthermore, the larger representation provides scope for more robust stand-alone analyses on this sub-group, which can be pursued in follow-up work,[3] in parallel to realising other research pursuits.

Challenges in model validation and emergent response

The online survey deployed in this study included three questions to measure *awareness* of hydrogen. It is recommended that constructs are formed from at least three indicators, however, reliability and validity could not be established in this case.

[3] Notably, in cases where pooling datasets is permissible, such as for the MEG and FSG in the adoption model (see Section 5.6.3), the availability of larger sample sizes can strengthen statistical power when conducting MGA.

Specifically, a third measure of awareness (AWR3) was dropped to retain the construct: *Are you aware that the UK government has a Hydrogen Strategy*? Consequently, the Domestic Hydrogen Acceptance Model (DHAM) has a limitation in capturing the cognitive dimension of domestic hydrogen acceptance as intended. Moreover, it proved unviable to model *objective knowledge* of hydrogen as originally planned and specified within the unified theory of domestic hydrogen acceptance (see Section 7.3 and Fig. 2-18).

At the theoretical level, objective knowledge was conceptualised to consist of 'technical' and 'general' knowledge of hydrogen, which were each represented by five question items in the survey. However, construct validity could not be achieved following all plausible attempts to combine different survey items, therefore, objective knowledge was excluded from the model. Nevertheless, *subjective knowledge* of hydrogen was included, albeit as a single item construct. Overall, these specific constraints meant that hydrogen awareness could not be modelled as an exogenous construct predicting objective and subjective knowledge, respectively.

This development changed the dynamics of the hydrogen acceptance model explored in Chapter 4, which is accordingly characterised as a 'baseline' model, since all constructs are exogenous, while domestic hydrogen acceptance is the sole endogenous construct. This decision was taken to overcome the reported limitations of capturing the cognitive dimension of domestic hydrogen acceptance in a more robust way, as theorised. Furthermore, at the practical level, it proved more logical to first explore the direct effects of all antecedent constructs, with a view that subsequent research should explore more complex dynamics. The same approach was taken when modelling domestic hydrogen adoption in Chapter 5.

Additionally, and reflecting the experience with modelling Awareness, the Perceived Costs (PC) construct developed in the PLS-SEM phase had two indicators, focused on economic (PC1) and social costs (PC2). A third measure of environmental costs (PC3) was dropped since convergent and discriminant validity could not be achieved, which in turn influenced the structural model. This discrepancy meant that perceived benefits and perceived costs could not be compared as intended, reflecting the imbalance between the former construct with three indicators and the adjusted PC construct with two indicators. In response, the adoption model proposed in Chapter 5

operationalised the two available indicators to form the construct, Perceived Socio-economic Costs (PSC) as more accurate reflection.

The limitations and adjustments discussed here are typical to PLS-SEM, especially when traversing uncharted territories in modelling an emerging energy technology such as hydrogen home appliances. However, the differences between the nature of the hydrogen acceptance model explored in Chapter 4 and the subsequent adoption model presented in Appendix K had implications for the PLS-MGA performed in Chapter 5. Following the MICOM procedure, it emerged that partial measurement invariance could not be achieved for cognitive constructs (i.e. awareness and knowledge), which inhibited the scope for multigroup analysis (MGA). By contrast, for the adoption model, the MICOM procedure established partial measurement invariance for all path relationships between all sub-groups.

As a result, Chapter 5 reflects this limitation and subsequent research decision, which was to focus exclusively on group differences regarding domestic hydrogen adoption potential. Since the adoption model retains three of the endogenous constructs included in the acceptance model (i.e. perceived costs, production perceptions, and safety perceptions), the findings are partially transferable to the earlier stage of broader attitudinal acceptance, ahead of behavioural acceptance in terms of adoption decision. As a result, there are multiple research avenues to explore in future models, which are summarised next.

Future research agenda in SmartPLS

Mediation analysis

Firstly, mediation analysis presents a rich area for further distilling the interactions between hydrogen acceptance/adoption constructs, as reflected by prior work engaging with energy technologies [12,13] including hydrogen [14–16]. Specifically, researchers employ mediation [17] to examine whether “a mediator variable to some extent absorbs the effect of an exogenous on an endogenous construct in the PLS path model” [18]. Future studies should explore the mediating role of constructs such as perceived benefits, as specified within Chapter 2 (see Fig. 2-18).

For example, it can be hypothesised that perceived benefits mediates the relationship between exogenous constructs (e.g. technology and production perceptions) and domestic hydrogen acceptance/adoption. Accordingly, PLS-SEM practitioners can

explore a range of new relationships to test whether full mediation, partial mediation, complementary partial mediation, competitive partial mediation, or no mediation is detected within the structural model [19,20], which will support deeper insights.

Moderation analysis

Moderation analysis also presents a critical area for developing further insights on the dynamics of domestic hydrogen acceptance and adoption. As described in the literature [18,21,22], moderation occurs when the effect on an exogenous on an endogenous construct is not constant but depends on the values of a third variable construct (i.e. the moderating variable). Moderation analysis is critical to the advancement of theory, as reflected by the uptake of its application in recent years [21,23]. In future studies, researchers can examine the moderating effects of a range of categorical and continuous variables [23] to advance knowledge on the topic.

Necessary condition analysis

Dul [24] developed necessary condition analysis (NCA) as methodology for identifying the necessary conditions for achieving a target outcome, which was discussed in the organisational context wherein determinants such as resources and efforts can drive a goal such as better company performance. The underlying premise of NCA is as follows: a necessary determinant must be present to achieve a target outcome, but its presence alone is insufficient to secure that outcome; therefore the 'necessary condition' is needed to offset the prospect of certain failure [24]. Put another way, the integration of NCA into PLS-SEM can enable researchers "to identify the ('must-have') factors required for an outcome, that is necessity logic, as well as the ('should-have') factors that contribute to a high-level, namely additive sufficiency logic" [25].

The efficacy of NCA has been demonstrated in diverse contexts such as public transport use in four northern European countries [26] and consumer purchase behaviour in Iran [27]. Hydrogen acceptance researchers can follow suit by combining NCA with PLS-SEM to test the theoretical foundations of the DHAM and STEEP Framework more precisely, thereby advancing efforts to increase the predictive power of models [28,29]. The practical implications of NCA are substantial in promoting more actionable insights for policy makers and stakeholders [25], which can be understood alongside results from IMPA [27]. Critically, NCA provides a direct means for verifying

which acceptance/adoption constructs may presents bottlenecks [24,26] for supporting the deployment of hydrogen homes.

Testing for unobserved heterogeneity in PLS-SEM

In addition to testing for mediation and moderation, and conducting NCA, researchers can employ measures to test for unobserved heterogeneity in the inner (structural) model [30,31]. While moderation analysis and MGA assume that the source of heterogeneity is known, in many cases this source may be unknown a priori [32]. Whereas heterogeneous data structures can be explained by observable characteristics, such as group membership in this study, unobserved heterogeneity may also present within the dataset [33,34] and present additional insight unto between-data group differences [34].

As articulated by Becker et al. [33], unobserved heterogeneity should be identified and treated to support correct estimation of the PLS path model. Researchers can combine finite mixture partial least squares (FIMIX-PLS) analysis [35] and PLS prediction-oriented segmentation (PLS-POS) [33,36] to detect whether hidden segments exist within the sample. Implementing this approach in future research can support robust latent class analysis [37], ahead of subsequent multigroup analysis in cases where unobserved heterogeneity is detected [30].

Modelling higher-order constructs

The STEEP Framework demonstrated the efficacy of aggregating lower-order constructs (LOCs: i.e. boiler performance and hob performance) into a higher-order construct (HOC: i.e. technology perceptions)[4] which was modelled as reflective-formative [38]. Implementing this technique can support theoretical parsimony, finer levels of abstraction [32,39], while reducing model complexity (i.e. number of structural paths) and averting the risk of confounding effects such as multicollinearity [18]. Future studies may explore modelling different hydrogen production pathways (e.g. ‘blue’, ‘green’ and nuclear) as LOCs of production perceptions. Another important research trajectory lies with exploring the dynamics of social trust, wherein several LOCs can be proposed to represent components such as institutional [40,41], competence, and

[4] Also referred to as hierarchical component models.

integrity trust [42–44]. For example, trust in the government, energy sector, and industry can be modelled as LOCs.

Additionally, third-order constructs composed of two second-order dimensions may also be explored, such as in the study of AlNuaimi et al. [45]. For example, this approach may prove viable in conceptualising ‘hydrogen experience’ as a higher-order construct, composed of ‘awareness’ at the second-order dimension, and subjective knowledge and objective knowledge at the third-order dimension. Accounting for these interactions would extend the premise of the unified theory of domestic hydrogen acceptance (see Fig. 2-18) in a novel way, while examining the importance of cognitive processes in explaining and predicting hydrogen acceptance and adoption. In exploring the potential for HOCs, researchers should test the validity of available LOCs (i.e. reflective-reflective; reflective-formative; formative-reflective; and formative-formative), while confirmatory tetrad analysis [46] can be employed to test the validity of formative constructs.

Notably, the application of HOCs supports the opportunity to develop specific models, which can be tested independently. For example, a model focusing exclusively on the role of environmental attitude in explaining and predicting hydrogen acceptance/adoption may be developed through a combination of constructs, including a focus on production perceptions. Additionally, a trust-based model can be examined as previously described, while further exploration into the emotional aspects of hydrogen acceptance and adoption can be realised by applying a multi-dimensional approach, as found in the work of Beaudry [47] and Kulviwat [48]. Such research avenues will afford ample opportunity to develop new survey instruments and corresponding indicators for a wide range of constructs. As an illustrative case of developing new survey instruments to improve the representation of constructs, researchers may start by exploring perceived comprehensive costs in the more extensive way, as suggested in Section 4.6.6.5.

Table Q-1. Survey instruments for measuring perceived comprehensive costs.

No.	Statement (for measuring via a Likert scale)
Q1	• Switching to a hydrogen home will increase my risk of experiencing financial debt
Q2	• Switching to a hydrogen will increase my vulnerability to fuel poverty
Q3	• Switching to a hydrogen home would make decisions around heating and eating more challenging
Q4	• Switching to a hydrogen home would compromise energy security
Q5	• Switching to a hydrogen home would compromise my ability to keep warm in winter
Q6	• Switching to domestic hydrogen would make the UK more dependent on energy imports
Q7 (a–c)	• Overall, switching to a hydrogen home is a risky proposition for: the UK economy; local communities; for me personally

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