International Journal of Hydrogen Energy 60 (2024) 1170–1191

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Hopes and fears for a sustainable energy future: Enter the hydrogen acceptance matrix

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ARTICLE INFO

Handling Editor: Dr Mehran Rezaei

Keywords:
Consumer acceptance
Domestic hydrogen energy
Energy transition
Fuel poverty
Hydrogen economy
Sustainable futures

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.

1. Introduction

Hydrogen is widely recognised by international policy makers as a critical energy vector for supporting climate change commitments [1,2] and associated net-zero targets [3,4]. Several hydrogen energy technologies (HETs) for industrial [5,6] and transport applications [7,8] may prove crucial to national energy transitions [9–11], and the wider global decarbonisation effort [3,12]. Additionally, hydrogen-fuelled appliances could help decarbonise residential heating and cooking [13,14], alongside other technologies such as heat pumps [15,16] and induction hobs [17].

In support of net-zero ambitions [18,19], low-carbon HETs for domestic heating and cooking purposes [14] have attracted policy interest in countries historically reliant on natural gas, such the UK [20–22], the Netherlands [23,24], and bordering European countries [25–27]. In viable geographies, it may prove feasible to supply hydrogen to homes by repurposing parts of the existing natural gas grid, in conjunction with establishing new hydrogen-dedicated pipelines [16,28,29].

Notably, the UK has emerged as a frontrunner country regarding the prospective transition to 'hydrogen homes' [30,31]. This status is well-reflected in the literature by a growing number of studies concentrated on techno-economic factors [15,16,32,33] and policy making [29,34], as well as consumer acceptance in the UK context [14,31,35,36]. Similarly, international evidence on the hydrogen economy is gradually expanding [37–40], with calls for cross-country studies on socio-technical barriers to the domestic hydrogen transition [28]. Despite recent advancement towards a better understanding of social acceptance in various contexts [41–45], few studies have explored how existing gas users perceive prospects of adopting hydrogen-fuelled appliances [13,14,46].

Social acceptance is set to play a critical part in shaping the transition to hydrogen homes [35], as reflected by the diffusion of other emerging energy technologies [47–49] such as smart home devices [50,51]. Traditionally, social acceptance has been examined in relation to political, market, and community dimensions [52–54], with more recent contributions extending this lens to encompass attitudinal and behavioural factors in the context of hydrogen homes [35,36]. However, given the nascency of hydrogen appliances, scholars are yet to validate assumptions drawn from previous insights into other low-carbon residential energy technologies, wherein several latent dimensions underpin social acceptance [55–58].

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https://doi.org/10.1016/j.ijhydene.2024.02.247
Received 2 October 2023; Received in revised form 10 February 2024; Accepted 18 February 2024
Available online 26 February 2024
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Nomenclature

BEV	Battery electric vehicle
BLG	Baseline Group
DoI	Diffusion of Innovation
FSG	Fuel Stressed Group
GDNOs	Gas Distribution Network Operators
HET	Hydrogen energy technology
HFCV	Hydrogen fuel cell vehicle
HFS	Hydrogen fuelling station
IQR	Interquartile Range
MASEM	Meta-analytical structural equation modelling
MEG	Moderately Engaged Group
PV	Photovoltaic
RET	Renewable energy technology
UK	United Kingdom
VEG	Very Engaged Group

Among emerging approaches, public understanding of hydrogen energy has been examined through the lens of social representations theory, revealing how consumer perceptions are shaped by "diverse influences along an individual-social continuum," spanning "personal, social, emotional, and symbolic levels of understanding and acceptance" [59]. Alongside knowledge and awareness, emotion plays a role in the social representation of hydrogen, which is co-constructed by different knowledge systems [59]. Likewise, when examining mobile generators powered by green hydrogen, Smith et al. [60] highlight how consumer perspectives are situated across a spectrum; ranging from positive to negative, and passive to active responses [61].

The notion of an 'acceptance spectrum' can be traced to Schweizer-Ries' [62] examination of renewable energy technology (RET). The proposed spectrum was subsequently formalised into a 'social acceptance matrix' by Friedl and Reichl [63] when examining renewable energy infrastructure and was recently extended to the case of hydrogen homes by Gordon et al. [36]. With these contributions in mind, this research conceptualises and characterises this spectrum as the 'domestic hydrogen acceptance matrix', which is explored and expanded in the analysis. Given the nature of domestic hydrogen – as an emerging technology with corresponding upstream and downstream impacts [46] wherein adoption is actualised at the household level [36] – the dynamics of social acceptance should be explored through engaging directly with consumers [39,43,64].

Drawing on results from a broadly nationally representative online survey, this study had three research objectives: (1) to demarcate the configuration of the domestic hydrogen acceptance matrix through analysis of extensive qualitative data; (2) to quantify the level of observed consumer heterogeneity regarding domestic hydrogen acceptance across different consumer segments; and (3), to test whether environmental and technology engagement have statistically significant effects on consumer attitudes towards hydrogen homes. The stated objectives feed into the underlying aim of the study, which is to advance conceptual and empirical understanding of the emerging contours of domestic hydrogen acceptance to support strategic decision-making.

The paper is structured as follows to achieve its aims and objectives. Following this introduction, Section 2 develops hypotheses for the study through literature review, while Section 3 introduces the theoretical foundations of the domestic hydrogen acceptance matrix. Section 4 describes the research approach, defining the study as an integrative, mixed methods analysis. Subsequently, Section 5 discusses consumer perspectives towards hydrogen homes, with Section 6 evaluating the proposed hypotheses by examining predictors of domestic hydrogen acceptance. Section 7 discusses the implications of the results, while Section 8 concludes with policy and research recommendations.

2. Literature review and hypotheses

Environmental awareness, technology engagement, and attitudes towards adopting new energy innovations have been shown to influence consumer support for a wide range of low-carbon technologies. For example, Ball [65] 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 [66]. Likewise, Plötz et al. [67] found that pro-environmental attitude ($\beta = 0.524$) and technological affinity ($\beta = 0.354$) have driven early adoption of electric vehicles in Germany, while Wolf and Seebauer reported similar findings among adopters of electric bicycles in Austria [68]. In response, the following sub-sections review these areas to develop hypotheses for this analysis.

2.1. Environmental interest and engagement

The literature broadly suggests that environmental attitude, referred to in different contexts in terms of concern [69], awareness [47], consciousness [70], or engagement [55], among other phrases, is a positive driver of energy acceptance and technology adoption. Notably, the influence of environmental concern as a driver of early adoption holds firm across other contexts such as transportation [68,71–73] and agriculture [74–78].

In the context of battery electric vehicles (BEVs), Wicki et al. [79] noted that 33 out of 38 quantitative studies reported a positive correlation between environmental attitudes and consumer acceptance. Furthermore, Ferreira et al. [50] showed that environmental awareness may reduce the need for trial or experience with smart energy technologies, which would in turn facilitate faster adoption rates. Notably, Vand et al. [80] found that increasing consumer awareness about the issues of non-green energy technologies in Shanghai persuaded 97% of survey respondents (N = 232) to change to cleaner electricity sources, albeit in accordance with their monthly income in 71% of cases.[1] Through a meta-analytical structural equation modelling (MASEM) approach [81], Schulte et al. [69] reported medium to large correlations between environmental concern and residential solar PV adoption. Additionally, solar PV adoption in Australia has been linked to pro-environmental attitudes [82].

Moreover, in the domestic energy context, Nakano [83] found that environmental consciousness positively influenced the uptake of energy-efficient homes among Japanese communities. A stronger environmental worldview has also been shown to increase intention to use a household energy management system in the UK context [84]. Additionally, based on a weight and meta-analysis using 44 articles and 48 datasets, Neves et al. [47] showed that environmental awareness is among the principal drivers of sustainable technology acceptance. Supporting these findings, Table 1 summarises additional results on the relationship between environmental attitude and energy acceptance across a range of technologies and country contexts.

Hydrogen acceptance studies also present findings that support the evidence base summarised in Table 1. For example, Kang and Park [95] found that environmental concern had a positive effect on purchase intention for hydrogen fuel cell vehicles (HFCVs) in South Korea. In the German context, Emmerich et al. [96] observed that environmental self-identity had a positive indirect effect on general (i.e. socio-political) acceptance for hydrogen fuelling stations (HFSs). Similarly, Harichandan et al. [97] indicated that Indian consumers may be motivated to purchase HFCVs due to environmental concern and as a means for symbolising environmental consciousness [98].

[1] Specifically, 26% of respondents were willing to change exclusively to renewable electricity regardless of monthly income; whereas other respondents expressed willingness to change partially, although the distribution of renewable and non-renewable electricity was undefined in the study.

Table 1
Summary of findings on the relationship between environmental attitude and energy acceptance.

Study	Technology examined	Country context	Relationship between environmental attitude and energy acceptance
[85]	Battery electric vehicles	Malaysia	• Environmental concern increased adoption intention
[70]	Eco-friendly smart home services	China	• Environmental consciousness positively predicted consumers' adoption intention
[86]	Renewable energy technologies	Finland and Poland	• A lack of environmental awareness creates a significant bottleneck to market acceptance and commercialisation
	Renewable energy technologies	Ghana	• Environmental awareness proved the most significant predictor of intention to use renewable energy
[87]	Residential micro-generation technologies[a]	Greece	• Positive relationship between pro-environmental behaviour and technology installation
[88]	Smart thermostats	Portugal	• Pro-environmental behaviour had a positive influence on intention to use and recommend the technology
[89]	Green electricity	Germany	• Consumer attitudes towards environmental protection issues dictates propensity to adopt green electricity, irrespective of individual power consumption
[65]	Solar rooftop PV	Sweden	• Early adopters are more driven by non-financial motives including environmental concern than later adopters[b]
[90]	Solar rooftop PV	Taiwan	• Environmental values had a positive impact on ecological lifestyle and adoption intention
[91]	Solar rooftop PV	Saudi Arabia	• Climate change awareness increased social acceptance
[92]	Solar rooftop PV	Sweden	• Environmental awareness positively influenced solar PV adoption
[93]	Solar rooftop PV	United States (New York)	• Environmental motivations proved slightly more important than economic factors for adopters
[94]	Solar rooftop PV	Iran	• Environmental concern positively increases the probability of technology adoption

[a] Biomass boilers, ground source heat pumps, micro wind, solar PV, solar thermal.
[b] Operationalising Green Party voting as a proxy for environmental concern.

For Danish respondents, willingness-to-pay for HFCVs was positively influenced by environmental sensitivity [99], while awareness of environmental issues and attitudes towards energy were also found to predict HFCV purchase among Chinese consumers [100]. In view of the literature findings, the following hypothesis is proposed to examine the effect of environmental attitude on domestic hydrogen perceptions:

H1. Interest and engagement in environmental issues such as climate change will positively influence domestic hydrogen acceptance.

2.2. Knowledge and awareness of renewable energy technologies

Across a range of technology context and country case studies, knowledge and awareness of renewable energy technologies has been shown to increase consumer acceptance. For example, Park et al. [101] showed that understanding the smart grid had a positive influence on support for the technology among South Koreans. Among Italian consumers, Franceschinis et al. [102] found that knowledge has positive effect on willingness to pay for wood pellet-fired heating systems. Notably, the relationship was observed for both early adopters and the early majority, but did not hold true for laggards (i.e. late adopters) [102].

In the Jordanian context, awareness of smart homes has also been shown positively influence consumer acceptance and adoption [103]. Surveying non-users of solar rooftop PV in Malaysia, Lau et al. [104] found knowledge to be a positive predictor of intention to install the technology. Furthermore, based on a cross-comparative study spanning households in five European countries, Neves [55] showed that consumer engagement (i.e. individual awareness and interest) has the strongest effect on driving behavioural change towards adoption energy-efficient heating appliances.

Hydrogen acceptance studies report similar trends [37,46]. For example, Hienuki et al. [105,106] concluded that public familiarity HFSs, as derived via knowledge and experience, can strengthen social acceptance among the Japanese population. In the Danish context, Apostolou et al. [99] reported a positive relationship between consumer support for HFCVs and technology awareness, as well prior experience with hydrogen technologies. Meanwhile, Chen et al. [107] noted that correct product knowledge reduced consumers' uncertainty regarding hydrogen-electric motorcycles, which led to stronger purchase intentions.

Engaging with Scottish respondents, Smith et al. [60] reported that information provision about hydrogen generators and production had a positive effect on consumer support, foremost towards green hydrogen production. Additionally, Gordon et al. [64] identified a positive relationship between knowledge and awareness and support for hydrogen production in the UK. Furthermore, results from the same dataset determined that interest and engagement with renewable energy has a positive effect on domestic hydrogen acceptance [13]. Conversely, consumer scepticism towards HETs has been associated with a lack of knowledge, awareness, and direct experience [95,108]. Taking stock of these results, this study explores the following hypothesis:

H2. Knowledge and awareness of renewable energy technologies will positively influence domestic hydrogen acceptance.

2.3. Consumer innovativeness and adoption category

Following Rogers' Diffusion of Innovation (DoI) framework [109], the importance of adopter categories and attitudes towards technology innovation is well-documented in the energy transitions literature [110–112], and presents a focal point of interest for 'hydrogen futures' research [37,113–115]. These findings are supported by the wider literature on low-carbon energy technologies [83,116,117] and on HETs [99,107,108,118].

Rai et al. [119] showed that 'staying at the frontier of technological innovation' has promoted solar PV uptake in Northern California [119], while interest in the technical attributes of solar PV (i.e. technophilia) has proved more prevalent among early adopters in Western Australian [66]. Additionally, consumer innovativeness has been identified as important factor in accepting solar PV in Iran [94] and intention to adopt sustainable household technology in the United States [120]. Moreover, Lozano et al. [39] 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 [39]. In turn, this study examines whether propensity towards trying new technologies (i.e. 'consumer innovativeness') will predict attitudes towards hydrogen homes, as formulated in the following hypothesis:

H3. Interest in being an early adopter of new energy technologies will positively influence domestic hydrogen acceptance.

2.4. Cumulative effect of technology and environmental engagement

To complete the investigation, a final hypothesis is developed to reflect the potential synergies between technology and environmental engagement, as drivers of domestic hydrogen acceptance and adoption

potential. Notably, when examining the diffusion of sustainable small-scale energy solutions in Finland, Nygrén et al. [121] define 'green consumers' as being "motivated by willingness to solve environmental problems and to promote sustainable energy innovations and product development."

Relatedly, ecological lifestyle and consumer innovativeness have been shown to increase intention to install rooftop solar PV in Taiwan [122] and Pakistan [123]. Similarly, environmental concern and awareness of solar energy strengthened consumer willingness to use solar panels in China [124]. Among Malaysian consumers, Cheam et al. [125] found that environmentalism had a larger positive impact on adoption intention for rooftop solar PV than knowledge about the technology. Notably, Zeng et al. [126] explored consumer attitudes towards clean energy technologies in Pakistan, wherein environmental concern ($\beta = 0.245$), and moreover, green energy technology awareness ($\beta = 0.362$), proved positive predictors of social acceptance. Furthermore, technophilia and environmentalism have driven early adoption of solar PV in Australia [66]. Following findings from the solar energy acceptance literature and related green energy studies [126,127], the following hypothesis is proposed:

H4. The combined effect of technology and environmental engagement will positively influence domestic hydrogen acceptance.

3. The hydrogen acceptance matrix

Building on earlier contributions to the renewable energy acceptance literature [52,62,128], Friedl and Reichl [63] developed an acceptance matrix[2] to examine public perceptions of energy infrastructure projects in the context of Upper Austria. Friedl and Reichl [63] consolidated the view that social acceptance is constituted by a spectrum of potential responses, composed of actions (active and passive) and judgements (positive and negative); wherein active resistance against energy infrastructure projects is more frequent than active support for their implementation. Adhering to this framework and related contributions to the social acceptance field [129–132], Gordon et al. [36] developed the 'social acceptance matrix of domestic hydrogen', which contends that consumer perspectives operate dynamically: moving freely between different poles of a wide spectrum of responses, whereby multiple positions can be held simultaneously.

Furthering this premise, Fig. 1 develops a more intricate representation of the hydrogen acceptance matrix, which reflects recent advancements toward understanding the interrelated emotional dimensions [133] of low-carbon energy transitions [134–136]. For example, Huijts [133], and Martiskainen and Sovacool [134], explored positive emotions associated with HETs such as pride, joy, desire and gratitude, alongside negative feelings including anger, fear, and greed. Accordingly, a multi-dimensional framework is conceptualised, wherein the positive spectrum is composed of optimism, hopefulness, and curiosity towards domestic hydrogen. Conversely, negative attitudes entail cautiousness, scepticism, and pessimism. For completeness, the intersection of these perspectives captures a hydrogen neutral position.

While the literature on domestic hydrogen acceptance remains nascent [35,137], recent contributions have emphasised the inherent multi-dimensionality underlying consumer preferences for hydrogen heating and cooking technologies [13,64,138]. Critically, hydrogen homes may evoke a range of complementary or conflicting perspectives, which correspond to multiple points on the acceptance matrix. For example, one respondent may convey a mix of *optimism* and *curiosity*, while another is *curious yet cautious* (see Section 5.1.2). With this framework in mind, Section 5 determines the configuration of the domestic hydrogen acceptance matrix and the level of consumer heterogeneity across four distinct consumer sub-groups. Firstly, the methodological approach is outlined in Section 4, which also defines each of the consumer sub-groups composing the sample.

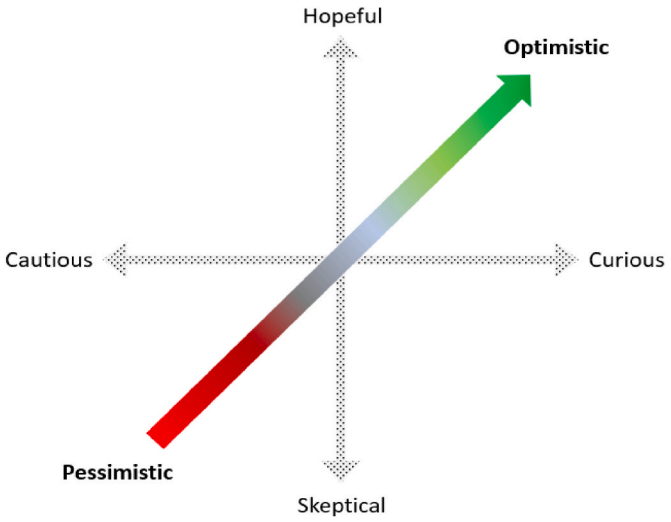

Fig. 1. The domestic hydrogen acceptance matrix.

4. Materials and methods

This section describes the materials and methods of the study, beginning with details regarding the sample characteristics and related multigroup analysis approach. Subsequently, filtering variables influencing the sample composition are explained, in addition to the data collection process and surveys instruments. Finally, details regarding the integrative, mixed methods research approach are provided.

4.1. Sample characteristics and multigroup analysis

The research approach follows an exploratory, sequential mixed methods design [139,140], which applies 'integration through building', whereby results from the initial (qualitative) data collection procedure informed the subsequent (quantitative) research phase [141,142]. Specifically, this study draws on findings from a series of online focus groups (N = 58) conducted by the authors between February and April 2022, which targeted specific consumer segments in the UK context [13,64]. Following the principal findings of the focus group phase [13,64,138], the online survey included four distinct sub-groups, which incorporated consumers with different levels of technology and environmental engagement (i.e. awareness, knowledge, or interest) and also accounted for households experiencing fuel poverty or high levels of fuel stress (see Table 2).

To approximate a nationally representative survey sample, quotas were set for the following variables: gender, age, housing tenure, housing type, and location. Other socio-demographic information was also recorded which excluded specific quotas, namely, education level, annual income, and number of occupants per household. Overall, the sub-sample analysed in this study (N = 1213)[3] succeeded in capturing each region of the UK and proved balanced in terms of gender representation,[4] while age, housing tenure, and housing type were somewhat nationally representative (see Table S1).

[2] Van Bilijon and Renaud [256] also presented an acceptance matrix mapping validated factors against the domestic technology adoption process in the context of mobile phone use.

[3] The full sample included 1845 responses, whereas 1213 participants provided qualitative answers.

[4] Although a response option was included for non-binary/third gender, and prefer not to say, we recorded full and valid responses only for male and female.

Table 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 = 308 (25.4)	• 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 = 232 (19.1)	• 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 = 246 (20.3)	• 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 = 427 (35.2)	• 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	1213 (65.7)	

The underlying rationale of the survey design was to secure a Baseline Group (BLG) which would account for around double the smallest group; optimally with a split of 40% for the BLG and 20% for each of the remaining sub-groups. However, the data collection process revealed that the Very Engaged Group (VEG) was harder to reach compared to other sub-groups, resulting in a minor degree of under-representation (~2.1%). Additionally, occurrences of incomplete answers or straight-lining responses resulted in a slightly reduced sample size for the BLG. Furthermore, it should be noted that the sub-sample for the Fuel Stressed Group (FSG: N = 246) included 16.3% of respondents who answered *yes* to living in fuel poverty, while the remainder qualified as fuel stressed (see Fig. S1).

It follows that the FSG presented within this study may be considered as a moderate representation of citizens living in conditions of fuel poverty. Therefore, a stronger representation of fuel poverty would prove desirable in follow-up research (see Table S2). To help visualise the filtering techniques, Fig. 2 provides the mean scores for each sub-group in relation to measures of technology and environmental engagement, which were evaluated according to a five-point Likert scale (Table S3 and Table S4). This data is drawn upon to support the analysis and testing of hypotheses in Section 6.

4.2. Inclusion criteria

A series of filtering questions were applied to target the intended population composed of homeowners (outright or mortgage) currently using both a gas boiler and hob in their property, who regard choosing their heating and cooking technologies as being at least *somewhat important*, and with at least a *moderate level* of involvement in purchasing these appliances (see Table S2). The rationale for this approach was to engage with consumers that are most likely to be affected by a prospective transition from natural gas to hydrogen, considering both direct and indirect impacts. In doing so, the sample accounts for the dynamics of financial decision-making, as well as personal responsibility for the property or other occupants within the household. By contrast, citizens renting their property from a private landlord, housing association or local authority were excluded due to their more restricted freedom or ability to take long-term decisions about investing in heating and cooking appliances.[5]

4.3. Data collection and survey instruments

The survey design was shaped by the following materials: a meta-review on domestic energy and hydrogen energy technologies [143] and supporting literature [35,36], and results from an online focus group study [13,64,138]. After programming the questionnaire in Qualtrics [144], subsequent feedback rounds from hydrogen experts and social scientists helped validate the survey instruments. The survey underwent a series of internal pilot tests and subsequent iterations ahead of distribution by a professional market research company.[6]

The survey included questions on specific areas of hydrogen acceptance, which are demarcated into the following categories: knowledge and awareness; production perceptions; technology perceptions (i.e. hydrogen boilers and hobs); financial perceptions; safety perceptions; perceived socio-economic costs; perceived risks (i.e. disruptive impacts); perceived community benefits; facilitating conditions; social trust factors; attitudinal preferences; emotional response; social acceptance; behavioural acceptance (i.e. willingness to adopt domestic hydrogen); and finally, willingness to pay for the domestic hydrogen transition. All survey items were measured using a five-point or eleven-point Likert scale. As part of the questionnaire, participants were also given a series of information provision items on hydrogen production methods, hydrogen activities in the UK, and hydrogen homes, including specific information on hydrogen boilers and hobs [13]. Overall, the survey duration was approximately 15–20 min.

As described in Table S4, this analysis concentrates specifically on emotional response (see Section 5) and social acceptance dynamics (see Section 6), alongside the qualitative data provided by responses to the following open-ended question which concluded the online survey:

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

Following data cleaning, around two-thirds of survey respondents (N = 1213) provided a valid response, with a relatively balanced response rate across sub-groups (M = 66.3%; SD = 3.0).[7] However, it should be noted that the VEG was more responsive than the BLG (~+7.0%), while taken together the VEG and the MEG (68.7%) had a higher response rate than the BLG and FSG (64.0%). To control for bias, calculations presented in this analysis are adjusted to represent the

[5] This methodological approach marks a departure from the focus groups analysis, which included the rental sector, albeit with modest representation (~12%).

[6] Firstly, a 10-day field (N = 160) was conducted by Savanta ahead of launch on October 6th, 2022.

[7] Response rates for qualitative answers were as follows for each sub-group: MEG = 67.2%; VEG = 70.1%; FSG = 64.9%, and BLG = 63.1% (see Table 1).

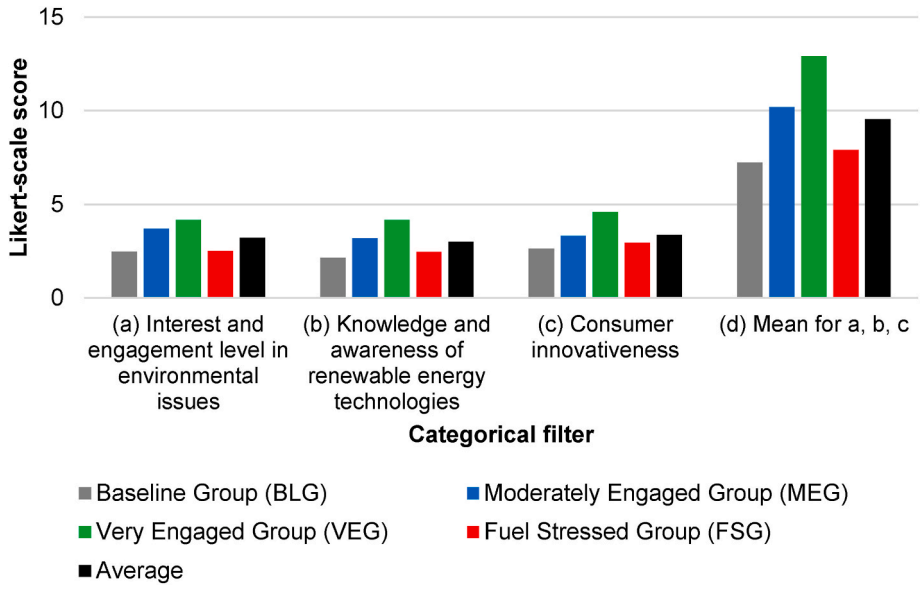

Fig. 2. Responses to filtering questions across consumer sub-groups.

relative frequency of responses, thereby enabling direct comparison of domestic hydrogen acceptance across sub-groups. While the main statistical analysis adheres to the data collected via qualitative responses, quantitative results from corresponding survey questions are incorporated to validate the findings (see Section 6). Accordingly, the study applies an integrative, mixed-method analysis.

4.4. Integrative mixed methods research

A mixed-methods research approach derives from intentionally combining quantitative and qualitative methods within the same analysis to help attain more nuanced and comprehensive findings, compared to either method in isolation [139,145]. Under an integrative, mixed-methods research design [146], a dialogue is established between qualitative and quantitative data [145] to generate 'deep structure' conclusions that enhance explanatory power [146].

Mixed-methods researchers have debated the ways in which qualitative and quantitative data can be integrated [147,148]. Fundamentally, data transformation sees one type of data converted into the other, which enables both strands to be analysed together [147]. Beyond data transformation, typology development occurs when one type of data produces a specific typology that serves as a framework within the analysis [147], in this case, the domestic hydrogen acceptance matrix. Typology development analysis is designed to examine "the homogeneity within and the heterogeneity between subgroupings of data" in respect to a specific dimension of interest, whereby the group explanatory variable (i.e. domestic hydrogen acceptance category) can be analysed statistically [147].

4.5. Integrated analytic phase: quantifying qualitative data

When quantifying qualitative data, scholars deliberately seek out the quantitative aspects in qualitative methods [149], which is an increasingly important aspect of mixed methods research in the social sciences [150–152]. Critically, quantification procedures must meet strict criteria of validity, reliability, objectivity, replicability, consistency, and adequacy [153]. Several viable methods exist for transforming qualitative survey data to standard quantitative variables [154,155], including regression analysis [156,157], variants of the probabilistic approach [158], and diffusion and composite indices [159], among other approaches [152,160,161].

In situations where multicollinearity and degrees of freedom estimates pose constraints, an alternative option for exploratory analyses is to estimate the percentage of each qualitative response as a function of its corresponding latent measure within the sample [154]. Latent variables refer to unobservable or unmeasurable constructs, whereas manifest variables are observed or directly measured [162]. Thus, the latent factor approach provides a valid method for estimating the underlying dynamics of the construct and informing the balance between optimistic and pessimistic responses [154], or the 'balance statistic' [163].

Following the latent factor approach, this study employs a merging procedure of data transformation [140,145,164], whereby qualitative statements provided by respondents at the end of the survey were quantified through two stages. Firstly, the qualitative dataset was rigorously analysed to identify factors of domestic hydrogen acceptance [165], through hybrid deductive-inductive coding [166,167]. This approach enables salient themes and patterns to emerge from within the data [168,169], which can be cross-checked to evaluate validity [170,171].

Subsequently, the qualitative dataset was analysed to map consumer responses to various positive, neutral, and negative factors to determine an overall position on the proposed hydrogen acceptance matrix (see Section 5). Thus, response patterns are interpreted to derive specific attitudes and emotional responses towards hydrogen homes (see 5.1.2). This approach adheres to the constant comparison method [170,171], as a highly iterative process wherein multiple stages were required to identify and validate the codes among the author team [172,173]. To support the findings, illustrative statements [174] are provided to capture specific consumer attitudes towards domestic hydrogen.

The data transformation and coding procedures were carried out using statistical software (SPSS 28.0). Initially, a basic understanding of the data was attained by way of frequencies, descriptive statistics, and general exploration. Subsequently, a series of non-parametric tests (Kruskal-Wallis H Test) and post-hoc tests were conducted to test for statistically significant differences between consumer sub-groups. Throughout the analysis, the adjusted ρ-value (Bonferri correction)[8] and the effect size (r) are reported. The formula for calculating the effect size is given below, where Z = standardised value for the test statistic; and n = sample size [175]:

[8] Calculated by dividing the original ρ-value by the number of analyses on the dependent variable.

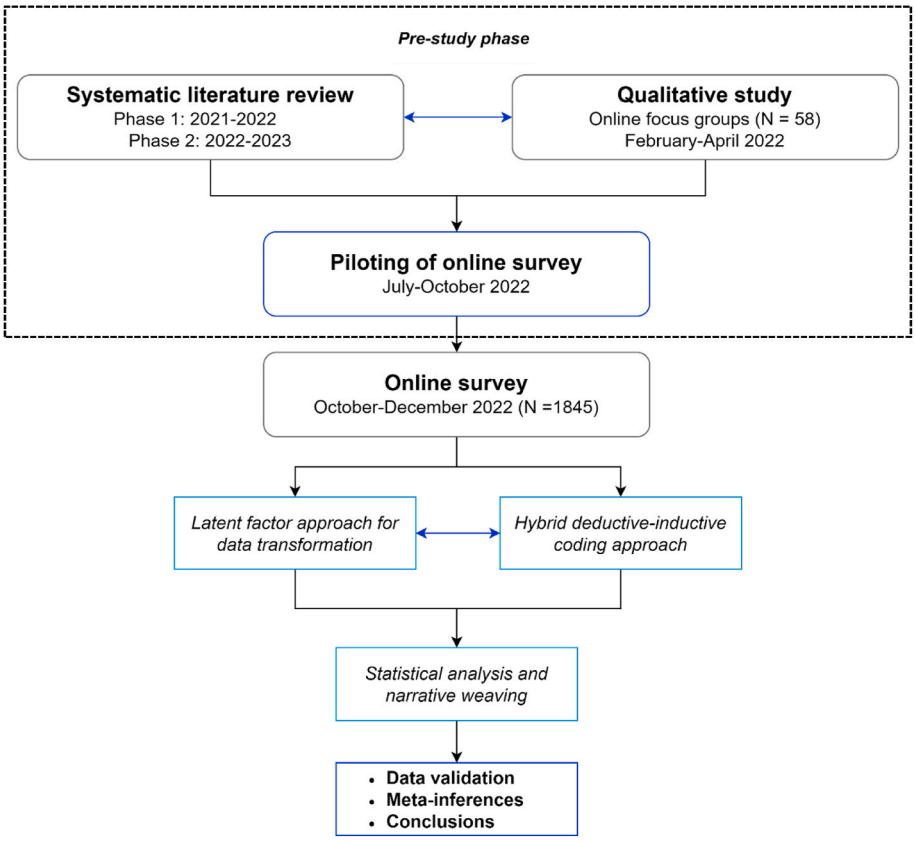

Fig. 3. Mixed-methods research design.

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

The following cut-offs are used in this study to evaluate effect size: small: 0.01–<0.08; moderate: 0.08–<0.26; large: >0.26 [176,177].

Broadly, the research procedure adheres to the method outlined by Castro et al. [146]: (1) coding the data; (2) establishing thematic categories; (3) converting the thematic categories into variables; (4) conducting statistical analysis; and (5) creating a coherent narrative by contextualising the integrated results and their meta-inferences. Sections 5 and 6 integrate the findings through a 'narrative weaving' approach (see Fig. 3) where qualitative and quantitative results are presented together thematically, as opposed to being divided within the same study or separated into different studies [140,178]. Foremost, narrative weaving provides a powerful tool for establishing the level of data fit between qualitative and quantitative findings.

5. Consumer perspectives of domestic hydrogen

This section reports and discusses the analytical findings on consumer perspectives of domestic hydrogen. Section 5.1 explores the parameters of the domestic hydrogen acceptance matrix in relation to one-dimensional and multi-dimensional consumer perspectives, while Section 5.2 validates the results through a multigroup comparison of consumer attitudes towards domestic hydrogen, which draws on supporting quantitative data from the online survey.

5.1. One-dimensional perspectives

From across the qualitative sub-sample (N = 1213), 81.8% of respondents (N = 992) expressed an inherently one-dimensional attitude towards domestic hydrogen. Following several rounds of preliminary analysis, responses were coded into one of seven categories (see Fig. 1) based on descriptive indicators which aligned to the following labels: *hydrogen pessimist*, *hydrogen sceptical*, *hydrogen cautious*, *hydrogen neutral*, *hydrogen curious*, *hydrogen hopeful*, *hydrogen optimist*.

As a starting point, the results were organised into positive and negative categories, taking the hydrogen neutral group as a reference point. Positive and negative perspectives accounted for 57.2% and 32.6% of responses, with neutral attitudes accounting for the remaining 10.2% of responses (see Table S5). As shown in Fig. 4, there was significant variation across sub-groups, with the VEG group proving significantly more positive (73.8%) than the BLG (42.5%).

Overall, the BLG was equally split between positive and negative responses, while neutral responses accounted for around 15.0%, compared to 5.1% for the VEG. Interestingly, the MEG and FSG shared a broadly similar response profile, although the FSG proved both more positive (+2.7%) and more negative (+2.9%) than the MEG. This suggests fuel stressed respondents may be slightly more polarised in their attitudes towards domestic hydrogen. Accordingly, neutral responses for the MEG were close to double that of the FSG (~11.0% and ~6.0%).

As a result, statistically significant differences were observed between the BLG and other consumer segments (ρ<0.001), with the largest differential traced to the BLG and VEG (r = 0.29). In line with the patterns observed in Fig. 4, the MEG and FEG proved highly comparable (r = 0.01), whereas a statistically significant difference was detected between the MEG and VEG (ρ = 0.042). Finally, the VEG and FSG presented a lower degree of heterogeneity (ρ = 0.097) compared to the MEG and VEG (see Table 3), which may be attributed to divergence regarding neutral responses.

Observed differences between consumer sub-groups were further explained by the distribution of specific one-dimensional positions across the sample (see Fig. 5). Across the positive spectrum of consumer perspectives, the BLG proved the least optimistic, hopeful, or curious (see Table S6). Conversely, this group proved the most cautious, sceptical, and pessimistic, as well as the most neutral. It can be inferred that a

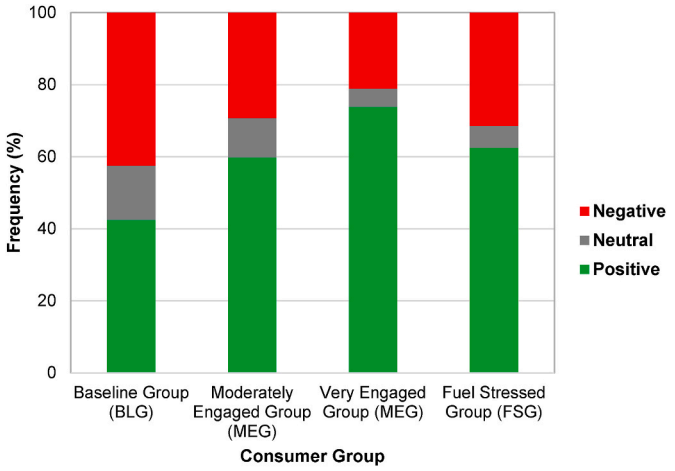

Fig. 4. Distribution of positive, negative and neutral perspectives of domestic hydrogen across consumer sub-groups.

Table 3
Pairwise comparisons between consumer sub-groups for positive, neutral, and negative perspectives of domestic hydrogen.

	BLG	MEG	VEG	FSG
BLG				
MEG	<0.001*** (0.17)[a]			
VEG	<0.001*** (0.29)	0.042** (0.13)		
FSG	<0.001*** (0.17)	1.000 (0.01)	0.097 (0.12)	

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

significant proportion of the UK population may be inherently undecided about domestic hydrogen; reinforcing the need for impactful information campaigns geared towards engaging the public with the prospect of the hydrogen homes [35,179].

In sum, heterogeneity was observed across the spectrum of one-dimensional consumer perspectives, albeit to varying degrees, with the *hydrogen optimist* category proving outright the most heterogenous perspective ($SD = 10.35$), followed by the *hydrogen hopeful* category ($SD = 5.78$). The remaining positive position, *hydrogen curious* ($SD = 3.89$) and two most negative perspectives, *hydrogen pessimist* ($SD = 3.78$) and *hydrogen sceptical* ($SD = 3.88$) showed similar levels of variation, as did *hydrogen neutral* ($SD = 4.62$). Foremost, the *hydrogen optimist* category composed of support from the VEG (44.1%) followed by the MEG (29.3%), compared to a mean of 29.5% across the sub-sample (N = 992). Consequently, the *hydrogen optimist* response exhibited the largest degree of variance, whereas the *hydrogen cautious* response showed minimal variance across sub-groups ($SD = 1.48$). The data suggests a divergence between hydrogen optimistic and hydrogen cautious attitudes, with the former proving heterogeneous, whereas the latter appears largely homogenous across the population.

It can be concluded that consumers attuned to environmental issues and engaged with RETs may prove more predisposed to supporting domestic hydrogen, whereas the attitudes of other consumer sub-groups appear more dispersed across the hydrogen acceptance matrix. These results suggest that technology and environmental engagement and conditions of fuel stress influence hydrogen acceptance in a comparatively positive direction.

5.1.1. Statistical analysis of one-dimensional perspectives

Responses to domestic hydrogen ranging from pessimistic to optimistic (see Table 4) were further analysed using SPSS 28.0. Firstly, a statistically significant difference is observed in levels of domestic hydrogen acceptance across consumer sub-groups: H (3, N = 992) = 58.24, $p<0.001$. As shown in Table 5, pairwise tests were statistically significant in five of the six comparisons, with the largest difference observed between the BLG and the VEG ($p<0.001$, $r = 0.33$). The mean scores and median ranks for each group were as follows: BLG ($M = 4.22$, $Md = 502$); MEG ($M = 4.86$, $Md = 627$); VEG ($M = 5.55$, $Md = 824$); FSG ($M = 4.81$, $Md = 560$).

The results were further validated following a merging procedure which created three categories: (1) Positive: *hydrogen optimist* and *hydrogen hopeful*; (2) Neutral: *hydrogen curious*, *hydrogen neutral*, and *hydrogen cautious*; and (3) Negative: *hydrogen sceptical* and *hydrogen pessimist*. The underlying rationale was to treat the *hydrogen curious* and *hydrogen cautious* categories as closer to neutral, thereby demarcating more distinct lines between positive and negative ends of the hydrogen acceptance matrix. Across the sample, the mean scores for each of the newly formed categories were as follows: Positive = 7.35, Neutral = 5.91, and Negative = 4.58.

The mean scores and median ranks for each group were as follows: BLG ($M = 2.10$, $Md = 426$); MEG ($M = 2.30$, $Md = 493$); VEG ($M = 2.59$, $Md = 605$); FSG ($M = 2.34$, $Md = 513$). As reported in Table 6, statistically significant differences in domestic hydrogen acceptance were observed across the consumer sub-groups H (3, N = 992) = 58.36, $p<0.001$. Pairwise tests showed significant effects in five of the six comparisons, with the largest difference similarly observed between the BLG and the VEG ($p<0.001$, $r = 0.33$). The findings further substantiate the extent to which technology and environmental engagement positively predict domestic hydrogen acceptance. Section 6 explores these observations in more detail by extending the analysis to the larger sub-sample (N = 1213).

5.1.2. Multi-dimensional perspectives

In addition to one-dimensional responses, 17.7% of participants (N = 215) expressed a two-dimensional attitude towards domestic hydrogen, which included 19 different combinations of perspectives from across the acceptance matrix (see Table S7). Overall, seven response types accounted for 80.5% of two-dimensional consumer perspectives. Regarding response types, the lowest variance was reported for *cautious but otherwise neutral* ($SD = 3.19$) and the largest variance for *optimistic yet cautious* ($SD = 9.07$), while the mean standard deviation was 5.33.

Among the expressed viewpoints, a dominant perspective emerged, namely, *hydrogen hopeful yet cautious* (see Fig. 6), which accounted for 38.1% of all two-dimensional responses ($SD = 8.32$). This position was most represented in the BLG (45.2%), followed by the VEG (43.2%) and the FSG (40.6%), whereas the MEG was least represented (25.8%). Nevertheless, participants from the MEG shared notable insights, with one respondent illuminating the dichotomy between fears and hopes for a sustainable hydrogen future:

> "*Bit nervous because I have a limited knowledge for energy use and only heard of major explosions involving hydrogen – makes me a bit fearful of accidents and if it is too much for homes. Conversely, I also understand that gas is finite and extracting and using it has terrible environmental consequences, so on balance, I would certainly support it for industry and possibly in homes*" (MEG 12).

These thoughts were strongly echoed by the following viewpoint, which offered reassurances to underlying reservations: "*Hydrogen is something new and people will be fearful, but if it can be rolled out to benefit the environment and hopefully take peoples' worry out of trying something new, that will benefit them too. It should be okay*" (MEG 35).

Additionally, seven respondents conveyed a multifaceted attitude towards domestic hydrogen which extended to at least three dimensions. While examples are limited within this study, such perspectives are potentially more representative of how different consumers may perceive domestic hydrogen if further probed to share their views. Considering that 34.4% of the participants (N = 637) failed to give a

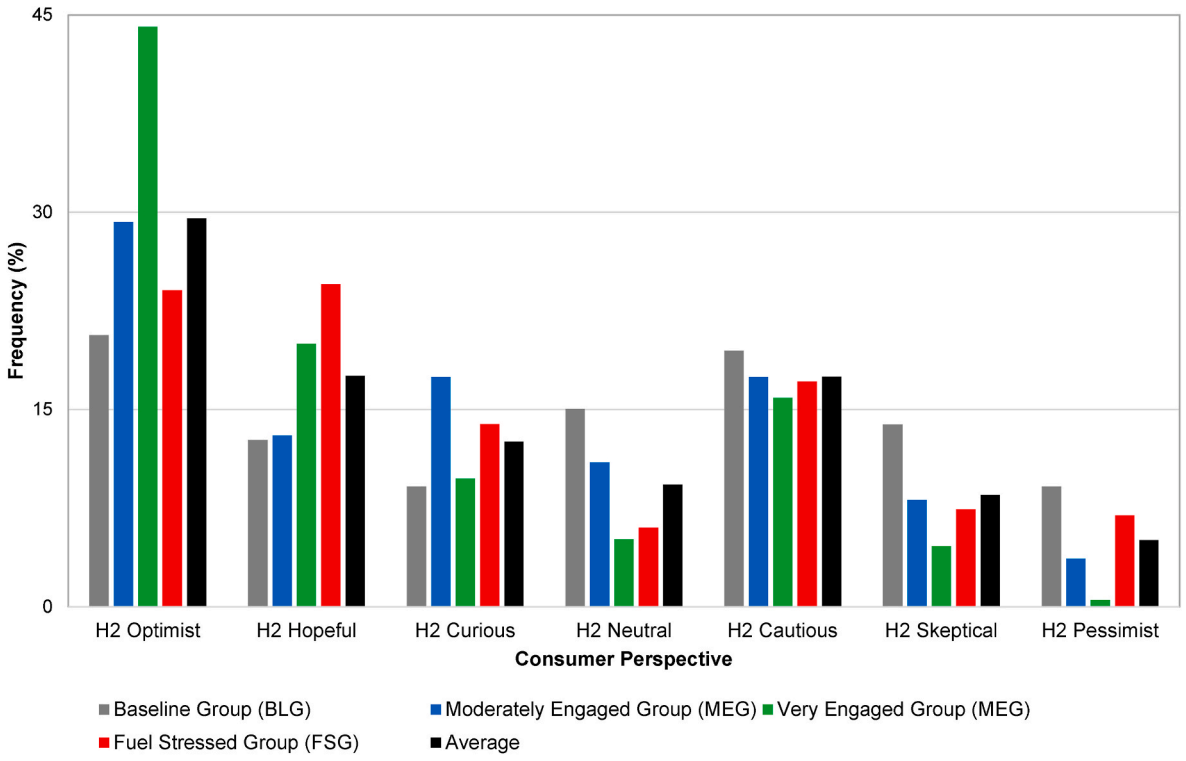

Fig. 5. Distribution of one-dimensional perspectives of domestic hydrogen across consumer sub-groups.

qualitative response, while the majority confined their answers to one-dimensional perspectives – sometimes restricted to brief statements – it is apparent that survey fatigue may have played a part in shaping the dataset presented in this analysis. In actuality, and as evidenced by the frequency and wide range of two-dimensional responses, it is anticipated that a significant proportion of UK homeowners may perceive different aspects of domestic hydrogen such as safety and cost distinctly.

It follows that an array of positive, negative, and neutral sub-factors will determine individual attitudes towards hydrogen homes, thereby shaping the overall configuration of the domestic hydrogen acceptance matrix. Table 7 exemplifies the extent to which such perspectives may prove nuanced and multi-dimensional, with a mix of positive and negative feelings expressed by respondents.

Reflecting the dynamics of the acceptance matrix, around 20% of respondents (N = 240) expressed a specific emotion towards domestic hydrogen in their qualitative responses. Six distinct feelings accounted for 93% and 88% of all positive and negative emotional responses, respectively (see Fig. 7). At the supportive end of this spectrum, positive and optimistic emotions were cited most frequently, while concern and worry dominated negative responses. In the case of worry and concern, these two sentiments were kept separate to reflect the language used by respondents. In all other cases, close synonyms were subsumed under one specific emotion. For example, fear included responses such as afraid and scared. Prior to subsuming various responses, a total of 12 positive and 23 negative feelings were observed, further reinforcing the richness of the hydrogen acceptance matrix (see Table S8 and Table S9). As a way of transmitting hopes and fears for a sustainable energy future featuring hydrogen, Table 8 provides illustrative examples of different emotions conveyed by respondents.

5.1.3. *Summary of findings on hydrogen perspectives*

Findings on one-dimensional perspectives towards domestic hydrogen show that seven positions, including a neutral mid-point, account for a wide spectrum of underlying attitudes. In summary, 82% of responses accounted for one-dimensional perspectives, while the remainder corresponded to multi-dimensional perspectives. The principal finding is that *hydrogen hopeful yet cautious* represents an eighth major category, which exceeds the *hydrogen pessimist* category, and is near equal to both *hydrogen neutral* and *hydrogen sceptical* categories, in terms of frequency of responses. Taken together, the eight perspectives shown in Fig. 8 represent nearly 90% of responses from across the sample.

The results consolidate the finding that positive attitudes towards domestic hydrogen are more represented across the overall sample, with optimism prevailing nearly 23% of the time. This breakdown is mostly explained by supportive attitudes among the VEG, and to a lesser extent the MEG, which increased the overall level of hydrogen acceptance from an otherwise more even split across positive and negative perspectives, as clearly observed in the BLG.

Having evaluated domestic hydrogen acceptance in relation to qualitative responses, the next section discusses these findings in comparison to quantitative results from specific question items in the online survey. In doing so, Section 5.2 validates the findings through a further application of data integration.

5.2. *Validating predictors of domestic hydrogen acceptance*

As a way of triangulating the findings and checking for robustness, this section investigates the results against two specific question items from the online survey. The first question examines behavioural acceptance (i.e. individual willingness to adopt hydrogen appliances), while the second examines social acceptance (i.e. a cumulative measure of socio-political, community, and attitudinal acceptance) [36]. Integrating statistical analysis on both aspects serves to validate key findings on the domestic hydrogen acceptance matrix and the factors which compose its configuration. Following tests to check for normality, (see Table S10, Fig. S2 and Fig. S3), a series of non-parametric tests were conducted to verify the results, thereby establishing the degree to which descriptive statistics drawn from the dataset correspond to the analytical findings regarding consumer perspectives of domestic hydrogen.

Table 4
One-dimensional consumer perspectives of domestic hydrogen.

Hydrogen perspective	Definition of consumer perspective	Illustrative statements (Respondent ID)
Hydrogen Optimist	Proponents of the domestic hydrogen transition, expressing attitudes of underlying optimism and positivity	• I believe hydrogen homes will be more effective and useful in the oncoming years as it will provide a safer energy supply not just for us but for the environment (BLG 85) • This survey has been an eye opener and I think one of the standout points for me is that it doesn't create carbon monoxide which is currently a silent killer. By switching to Hydrogen this could save a number of lives every year as well as being more eco-friendly (BLG 388) • 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 141). • This change is going to be beneficial to UK households and the country's effort to meet net-zero targets. I fully support it (FSG 220)
Hydrogen Hopeful	Supporters of the domestic hydrogen transition, expressing attitudes of hope towards developing hydrogen futures	• Exciting and hopeful for a cleaner energy source and less reliance on foreign gas (BLG 42) • It looks like hydrogen will be the fuel of the future. I hope the transition will be done in a fair and safe way (MEG 207) • I am hopeful that this new source of energy is not only better for the environment, but will be more affordable for homes (FSG 41) • I think it's probably the way forward to heating our homes and to cook with. It's renewable and sustainable (FSG 101)
Hydrogen Curious	Consumers interested to know more about hydrogen and supporting further exploration of the technology	• I think overall it's a very interesting topic. I'll keep my eye on more moving forward (FSG 103) • Didn't know much about it before. I feel a little more enlightened now and would be willing to change when needed if the price was comparable or better still (BLG 31) • Interesting and thought provoking and makes me realise I need to find out more (BLG 225) • I knew nothing about hydrogen or its future use, but now feel more informed and want to investigate further (FSG 79)
Hydrogen Neutral	Consumers expressing indifference towards the domestic hydrogen transition	• Neither am I agreeing or disagreeing to it, I have no further attitude towards it (BLG 297) • I don't have an opinion on this because every other person deals with it differently (VEG 68) • I don't have strong feelings. The government has responsibility (FSG 56) • Not decided about true benefits and negatives (FSG 182)
Hydrogen Cautious	Consumers reluctant to support the domestic hydrogen transition due to a range of reservations and concerns	• I am slightly concerned over safety issues and the cost of implementing this and where the funds would come from (BLG 83) • I don't know much about hydrogen. I thought I had heard about it being used for cars but might be wrong about that. I would need to understand a lot more about hydrogen to feel confident about its widespread use in the near future (BLG 95) • I don't know how safe I feel about it. We've grown up and only used natural gas until now, so it is quite a big change (MEG 90) • If hydrogen is a dangerous substance, then correct testing needs to be conducted to ensure it is safe before it is rolled out across the country. Costs should also be kept reasonable (VEG 126).
Hydrogen Sceptical	Rejecters of the domestic hydrogen transition, expressing attitudes of scepticism towards developing hydrogen futures	• Having seen a few items on news programmes concerning blue hydrogen, it seems to be a big ask to go for a 2030 push to start a major switch to hydrogen. Will it be a flash in the pan like fusion energy from water? (BLG 59) • Having seen the rollout and shutdown of hydrogen power fuelling stations for cars, I'm not sure about how effective other rollouts would be (BLG 60) • I am just unsure if it will work and how much it will actually save. I believe a lot of people will be sceptical about this too (VEG 57) • What alternatives are there to hydrogen and what happens to all the gas and electricity workers if it is introduced? They will be made redundant in greater numbers than jobs created. How much will the new boilers and hobs cost? How much will hydrogen cost in comparison to existing bills? (FSG 238)
Hydrogen Pessimist	Opponents of the domestic hydrogen transition, expressing attitudes of underlying pessimism and negativity	• Hydrogen sounds dangerous. The UK cannot rush to net zero, endangering and impoverishing us all. The UK could get to net zero tomorrow and it would have next to no impact on climate change at all, considering the UK contributes less than one percent of global emissions (BLG 70) • I don't like change especially when it costs even more. I'm sick of paying ridiculous prices for fuel and gas (BLG 98) • Comical that this is being considered as a solution or option with the problems it presents and its extremely low calorific value. We would have to burn so much more for the equivalent heat and with so much danger involved and years of disruption; with two pipes down roads instead of one and two gas supplies in the country instead of one. We need to go back to coal gas. We have the coal and the infrastructure here now (MEG 15)

5.2.1. *Social acceptance of domestic hydrogen*

As illustrated in Fig. 9, three aspects of social acceptance were evaluated using an eleven-point scale (opposed to supportive). The results further validate one of the principal findings from this study, namely, that the VEG is significantly more supportive of domestic hydrogen than baseline respondents (BLG), as well as other sub-groups (MEG and FSG). From a maximum theoretical score of 30 points, the mean total score was 19.97 (SD = 2.51, IQR = 3.81), with the VEG scoring highest (M = 23.31) and the BLG scoring lowest (M = 17.66). However, in this instance, there was a more pronounced gap between the MEG (M = 20.43) and FSG (M = 18.47). Corroborating previous observations, quantitative results separate the MEG and FSG more distinctly, with the former proving more supportive of hydrogen homes. This pattern is logical given the influence of technology and environmental engagement on hydrogen acceptance, vis-à-vis the VEG. Overall, the same rank order of support (VEG, MEG, FSG, BLG) is preserved when comparing social acceptance to willingness to adopt domestic hydrogen.

Table 9 summarises the main findings on consumer heterogeneity following a Kruskal-Wallis test, H (3, N = 1213) = 110.92, ρ<0.001, wherein the largest effect size was reported between the BLG and the VEG (r = 0.39), followed by the FSG and the VEG (r = 0.33). The mean scores and median ranks for each group were as follows: BLG: M = 5.80,

Table 5
Pairwise comparisons between consumer sub-groups for one-dimensional positions across the hydrogen acceptance matrix.

	BLG	MEG	VEG	FSG
BLG				
MEG	0.001*** (0.15)[a]			
VEG	<0.001*** (0.33)	0.001*** (0.18)		
FSG	0.008*** (0.14)	1.000 (0.02)	<0.001*** (0.20)	

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

Table 6
Pairwise comparisons between consumer sub-groups for positive, neutral, and negative categories.

	BLG	MEG	VEG	FSG
BLG				
MEG	0.013** (0.13)[a]			
VEG	<0.001*** (0.33)	<0.001*** (0.21)		
FSG	0.001*** (0.16)	1.000 (0.04)	0.002*** (0.18)	

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

Md = 502; MEG: *M* = 6.75, *Md* = 651; VEG: *M* = 7.50, *Md* = 790; FSG: *M* = 6.19, *Md* = 562.

It is noteworthy that socio-political acceptance scored higher (*M* = 6.75) than both community (*M* = 6.60) and attitudinal acceptance (*M* = 6.63) across all sub-groups, except for the VEG (see Fig. 9). Mirroring the patterns observed for willingness to adopt domestic hydrogen, results are highly consistent across different measures of hydrogen acceptance. However, there is also some indication that overarching public support for the domestic hydrogen transition may prove stronger than consumer acceptance at the local or individual level. Critically, the cancellation of planned hydrogen village trials for Whitby, Ellesmere Port (Northwest of England) [180,181] and Redcar in Yorkshire (Northeast England) [182,183] reflect a deficit in community acceptance for the domestic hydrogen transition [184,185].[9]

Events on the ground reflect the challenge of actualising hydrogen trials in parts of the UK. Consequently, Gas Distribution Network Operators (GDNOs) such as Cadent Gas [186,187] and Northern Gas Networks [188] face an increasing imperative to anticipate community- and household-level responses to hydrogen homes. Primarily, GDNOs are tasked with managing the technical risks associated with grid infrastructure, which is paramount to building positive safety perceptions of hydrogen during times of disruptive activities and perceived change. However, it follows that building consumer trust and enacting measures of procedural justice are equally important responsibilities in the context of local hydrogen trials [165,189].

5.2.2. Willingness to adopt domestic hydrogen

As displayed in Fig. 10, three aspects of willingness to adopt domestic hydrogen were measured according to a five-point Likert scale: *Not willing at all*, *Slightly willing*, *Somewhat willing*, *Very willing*, and *Extremely willing*. Across the sample, from a maximum theoretical score of 15 points, the mean total score was 9.15 (*SD* = 1.20, IQR = 1.33). The VEG proved the most supportive demographic (M = 10.83), while the BLG proved the least supportive (M = 8.01). Furthermore, and mirroring the results illustrated in Fig. 4, the MEG and FSG present similar mean scores (8.99 and 8.75).

Table 10 summarises the statistical findings following a Kruskal-Wallis test, H (3, N = 1213) = 135.88, $p<0.001$, wherein the largest effect size was reported between the BLG and the VEG (r = 0.44), followed by the FSG and the VEG (r = 0.38). The mean scores and median ranks for each group were as follows: BLG (*M* = 2.60, *Md* = 502); MEG (*M* = 2.97, *Md* = 627); VEG (*M* = 3.52, *Md* = 824); FSG (*M* = 2.77, *Md* = 560). As captured in Fig. 10, it follows that the VEG has the highest willingness to adopt domestic hydrogen appliances, followed by the MEG, FSG, and BLG, which is broadly consistent with results in Section 5. The area of some divergence in results is between the MEG and FSG, which are relatively aligned in terms of their qualitative response, but more disparate according to quantitative results.

Interestingly, across all sub-groups, willingness to adopt a hydrogen boiler before 2030 (*M* = 3.09) was marginally higher than willingness to adopt a hydrogen hob (*M* = 3.04) or hydrogen home before 2030 (*M* = 3.02). While this pattern is somewhat noteworthy, the overall result corroborates previous evidence which observed "no discernible difference between consumer willingness to switch to hydrogen cooking or heating" [13], which has also been reported in the Australian context [39]. Nevertheless, additional checks should be undertaken to determine whether it may be more prudent to focus communication campaigns on promoting the potential benefits of hydrogen heating, at least in the early stage of the transition.

5.2.3. Comparative assessment of pairwise results

To complete this part of the analysis, the previous results are triangulated by incorporating a comparison of pairwise tests and calculating the mean effect score (r), as reported in Table 11. The following relationships are observed in ascending order of effect size: FSG–MEG (r = 0.07), BLG–FSG (r = 0.12); BLG–MEG (r = 0.17), MEG–VEG (r = 0.22); FSG–VEG (r = 0.27), and BLG–VEG (r = 0.37). Thus, a small effect is observed between the FSG and MEG, as well as the BLG and the FSG, while a moderate effect is observed between the BLG and MEG, in addition to the MEG and VEG. By contrast, there is a large difference between the VEG when compared to both the BLG and the FSG.

Through a series of statistical tests, it has been shown that knowledge and awareness of RETs, interest and engagement in environmental issues, and interest in adopting new energy technologies are positive predictors of hydrogen optimism. Foremost, consumer heterogeneity is observed between respondents with high levels of technology and environmental engagement and respondents who are less than moderately engaged with these two interrelated areas.

Fig. 11 maps each consumer sub-group to an approximate position on the hydrogen acceptance matrix, thereby demarcating 'zones' of acceptance and resistance, and potentiality. In line with Fig. 5, It follows that the VEG is more aligned to hope and optimism, while the MEG is comparatively less optimistic yet still hopeful and curious. Similarly, the FSG transmit feelings of hopefulness which are characterised by a slighter higher degree of cautiousness than curiosity. Finally, the BLG is outright the most cautious, pessimistic, and sceptical sub-group.

Large effect sizes are observed in seven pairwise comparisons across the four Tables. For the combined results in the final column, all effect sizes are denoted by asterisks, with two results corresponding to large effect sizes (BLG–VEG, and VEG–FSG). The analysis shows the following consistencies: all pairwise comparisons between the BLG and MEG have a moderate effect size ranging from 0.13 to 0.21; effect sizes between the BLG and VEG are large, ranging from 0.33 to 0.44; effect sizes between the BLG and FSG are moderate with a lower bound of 0.08 and an upper bound of 0.16; effect sizes between the MEG and FSG are split between small and moderate, ranging from 0.02 to 0.13; effect sizes between the VEG and FSG are distributed between moderate and large, with a lower bound of 0.18 and an upper bound of 0.38; and most effect sizes between the MEG and VEG are moderate (0.18–0.28).

[9] In July 2023, increasing opposition culminated in a decision to cancel a long-planned hydrogen trial for around 2000 homes in Whitby village [180,257]. The decision led to significant pressure for a public vote on a parallel hydrogen trial in Redcar [258], which was subsequently cancelled in December 2023.

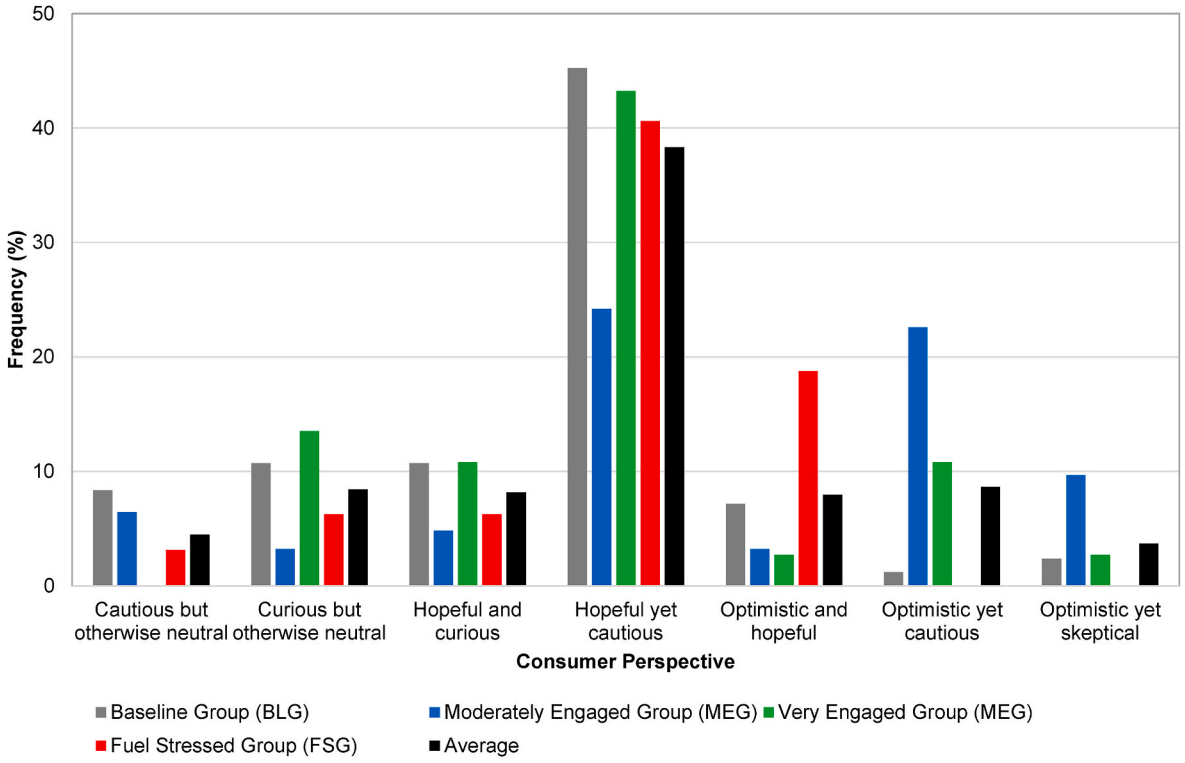

Fig. 6. Distribution of two-dimensional perspectives of domestic hydrogen across consumer sub-groups.

6. Predictors of domestic hydrogen acceptance

Through a merging procedure of data transformation – integrating qualitative and quantitative results – Section 5 explored the contours of consumer heterogeneity [165] in relation to four distinct consumer groups. The remainder of the analysis examines whether observed differences between consumers in respect to identified factors are statistically significant. Firstly, the previous results are extended by examining the association between social acceptance and willingness to adopt domestic hydrogen. In doing so, this section tests the relationship between identified factors and acceptance and adoption dynamics to answer the proposed hypotheses (**H1**–**H4**).

6.1. Relationship between social acceptance and willingness to adopt domestic hydrogen

The results demonstrate relative consistency in consumer attitudes towards accepting the domestic hydrogen transition and willingness to adopt hydrogen heating and cooking appliances (Figs. 9 and 10). Accordingly, social acceptance is positively associated with adoption intention, suggesting general acceptance of hydrogen at the socio-political and community level may precipitate conditions for subsequent technology adoption [108]. To explore the positive association between these two variables, a Spearman's correlation coefficient test is conducted, which supports the hypothesis: $r_s = 0.521$ (0.478–0.562), $N = 1213$, $\rho<0.001$). It follows that variance shared between hydrogen acceptance and adoption is 27.14%.

Next, the coefficients between categories and measures of hydrogen acceptance and adoption intention are examined to validate prior observations. Table 12 confirms that environmental interest and engagement (**H1**), and knowledge and awareness of RETs (**H2**), in addition to consumer innovativeness (**H3**) are positively and significantly associated with hydrogen acceptance and adoption willingness. Accordingly, the cumulative measure of these three variables (**H4**) reflects the same result. Based on guidelines provided by Gignac and Szodorai [190] and in view of related critiques concerning normative guidelines for interpreting coefficient values [191], the following conclusion can be drawn: the results indicate an at least moderate effect that is potentially powerful in both the short and long-term [192].

Critically, environmental interest and engagement is more strongly associated with domestic hydrogen acceptance compared to other variables, but has a comparatively weaker effect on adoption intention. This result is consistent with findings in the literature which suggest the influence of environmentalism may diminish as consumers move through the initial stages of the innovation-decision process [65,102]; from 'knowledge' to 'persuasion' and 'decision', ahead of 'implementation' and 'confirmation' [109,193].

6.1.1. Technology and environmental engagement

To examine the influence of psychological and attitudinal factors, a series of Kuskal-Wallis *H* tests and post-hoc tests are conducted. Firstly, the relationship between domestic hydrogen acceptance and technology and environmental factors proved consistent. As reported in Table 13, no statistically significant difference was observed between the two extremes: (1) Very Low and Low groups, and (2) High and Very High groups, whereas the eight remaining pairwise test comparisons proved significant at the 1% level ($\rho<0.001$). The effect of interest and engagement in environmental issues was slightly larger than that of knowledge and awareness of RETs for the most disparate groups: Very Low–Very High, and Low–Very high. These results demonstrate the positive influence of technology and environmental engagement on domestic hydrogen acceptance, thereby supporting the first two hypotheses. Moreover, the results further reflect observed consumer heterogeneity between the VEG and other sub-groups.

6.1.2. Consumer innovativeness

Consumer innovativeness may contribute towards domestic hydrogen acceptance and could provide a close proxy for adoption potential. To test this hypothesis, the five innovation categories specified within the survey (see Fig. 2) were recoded into three groups, which

Table 7
Three-dimensional perspectives of domestic hydrogen acceptance.

Respondent ID	Illustrative statement	Perspective
MEG 294	• Very interested to know more … wasn't aware of this but keen to support energy that helps reduce carbon emissions, but need to ensure stability across the network and ensure the poorer communities are not disadvantaged further.	Optimistic and curious, yet cautious
BLG 229	• Interesting to learn more about it as I knew little. Cost worries me. As does disruption. But overall, environmentally it sounds positive.	Hopeful and curious, yet cautious
BLG 254	• 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 395	• Unsure and slightly overwhelmed as I'm not technically minded, so struggle to understand all the ins and outs of it all. I think safety will be a big concern, but I would hope that vigorous testing would have taken place prior to the changes. I would like to see positive changes with regards to climate change, but living in a rural area I think it will be a long time coming to where I am.	Hopeful, yet cautious and sceptical
FSG 83	• I like the idea, but I think it is untested and that makes me nervous. It could fail a bit like hydrogen cars.	
BLG 114	• I feel too unsure about hydrogen to make any commitment at this stage, despite the environmental impact which have been discussed. The cost implications appear too much at present.	Cautious and sceptical, but otherwise neutral
MEG 49	• I am apprehensive about using hydrogen, but if proven to be as safe as natural gas, but better for the environment, what's the difference? But I doubt it will be affordable and I expect complications such as with solar panels or insulating foam.	

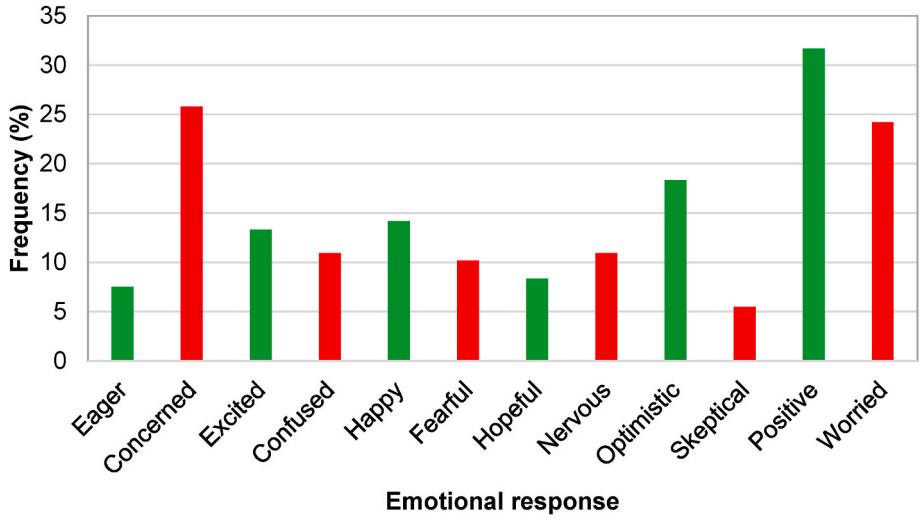

Fig. 7. Frequency of positive and negative emotional responses.

retained the mid-level but merged lower and higher categories. Thus, the original results (Minimum: N = 47; Low: N = 146; Medium: N = 634; High: N = 249; Maximum: N = 136) were transformed as follows: Low innovation level: N = 193; Medium innovation level: N = 634; and High innovation level: N = 385.

A Kuskal-Wallis test was performed on the newly formed groups to examine the influence of innovation category (i.e. consumer innovativeness) on domestic hydrogen acceptance: H (2, N = 1213) = 105.75, $\rho<0.001$. The rankings followed the predicted order with notable discrepancies between groups: Low innovation level (N = 193, Md = 431); Medium innovation level (N = 634, Md = 582); High innovation level (N = 386, Md = 737). Pairwise tests showed a statistically significant

Table 8
Positive and negative emotional responses to domestic hydrogen.

Emotional response	Illustrative statements (Respondent ID)
Eager	• I am eager to see hydrogen used as an alternative fuel (MEG 50).
Concerned	• 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 76).
Excited	• It sounds really good and great for our environment. I am very excited about it and definitely will be looking more into it. It is very important for me as a homeowner and also as a mother who is worried about child's future due to climate change (VEG 163).
Confused	• Rather confusing. Need to learn more about it. Price, safety, and climate are all important (BLG 333).
Happy	• I'm really happy there is an alternative to gas that is safe (VEG 135).
Fearful	• 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 369).
Hopeful	• I am hopeful to see how this develops in the future and what it may mean for our society and for our climate (BLG 74).
Nervous	• Feel quite nervous thinking about it, probably because it's something new (BLG 45).
Optimistic	• I am very optimistic about the future of hydrogen-powered homes and will be interested in investing (MEG 65).
Sceptical	• It's one energy that I don't know too much about. I am very sceptical (VEG 175).
Positive	• I am very positive about hydrogen and am willing to be a test home to convert from gas to hydrogen as soon as possible (VEG 65).
Worried	• Worried it might be expensive. Not sure about reliability, plus repair and maintenance cost will be higher, as its a new concept. In terms of house use installation, there will be flaws that will take years to perfect (FSG 240).

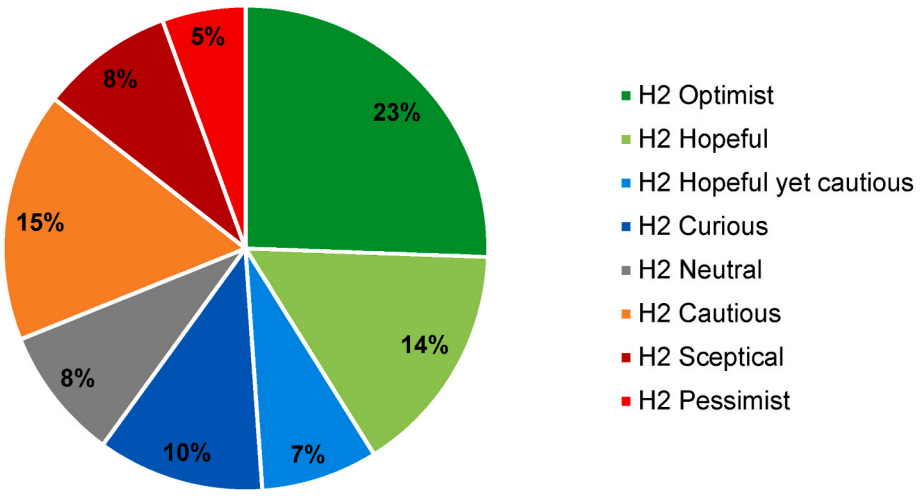

Fig. 8. Consumer perspectives towards domestic hydrogen across sample.

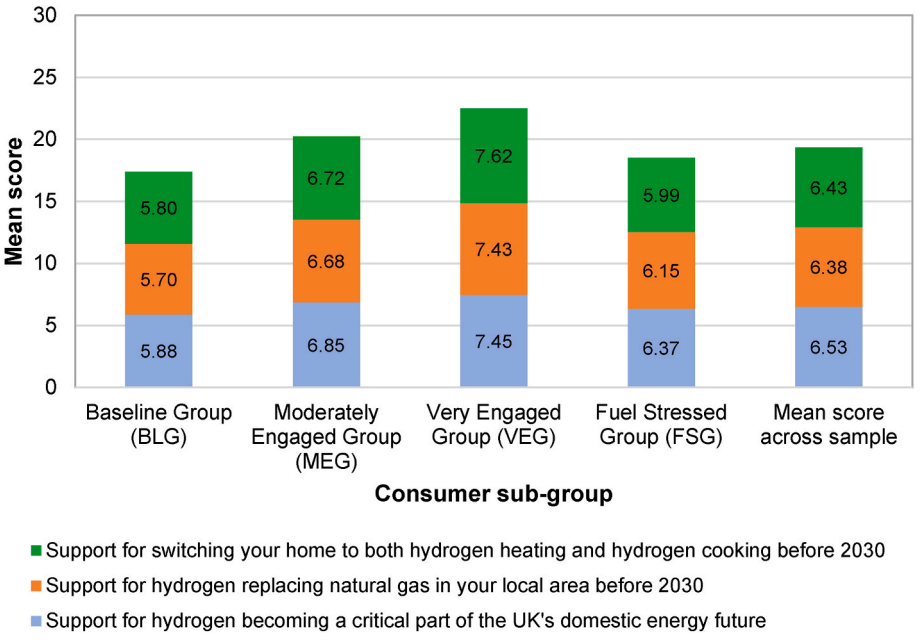

Fig. 9. Measures of domestic hydrogen acceptance.

Table 9
Pairwise comparisons between consumer sub-groups for domestic hydrogen acceptance.

	BLG	MEG	VEG	FSG
BLG				
MEG	<0.001*** (0.21)[a]			
VEG	<0.001*** (0.39)	<0.001*** (0.20)		
FSG	0.214 (0.08)	0.015** (0.13)	<0.001*** (0.33)	

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

relationship for each comparison: Low innovator and Medium innovator ($\rho<0.001$, $r = 0.18$); Low innovator and High innovator ($\rho<0.001$, $r = 0.41$); Medium innovator and High innovator ($\rho<0.001$, $r = 0.22$). Consequently, the greatest difference was observed between consumers with low and high innovation levels (see Table 13). The results support H3, confirming the positive influence of consumer innovativeness (i.e. interest in being an early adopter of new energy technologies) on domestic hydrogen acceptance.

6.1.3. *Cumulative influence of technology and environmental engagement*

To validate the results and further explore the configuration of the domestic hydrogen acceptance matrix, the following data transformation procedure was performed in relation to the cumulative technology and environmental engagement score of respondents (theoretical maximum = 15): (1) **Low**: Score of 7 and below; (2) **Moderate**: Score of 8 or 9; (3) **High**: Score of 10 or 11; (4) **Very High**: Score of 12 and above (see Fig. 2). The mean scores and median ranks for each group were as follows: Low: $M = 5.93$, $Md = 430$; Moderate: $M = 8.56$, $Md = 572$; High: $M = 10.42$, $Md = 682$; Very High: $M = 12.93$, $Md = 790$.

Carrying out a Kuskal-Wallis test on the transformed data confirmed a statistically significant relationship between all six group pairings: $H(3, N = 1213) = 110.92$, $\rho<0.001$. As reported in Table 13, the effect size was strongest between the Low and Very High groups ($r = 0.51$),

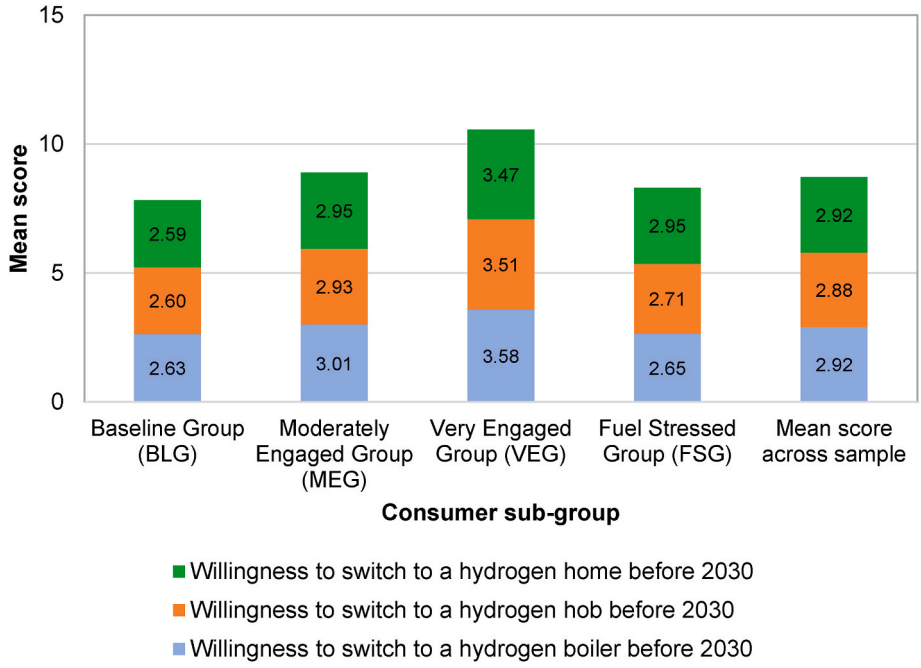

Fig. 10. Measures of domestic hydrogen adoption.

Table 10
Pairwise comparisons between consumer sub-groups for willingness to adopt domestic hydrogen.

	BLG	MEG	VEG	FSG
BLG				
MEG	<0.001*** (0.18)[a]			
VEG	<0.001*** (0.44)	<0.001*** (0.28)		
FSG	0.217 (0.08)	0.025** (0.10)	<0.001*** (0.38)	

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

followed by the Low and High groups ($r = 0.36$), whereas the effect size between the Moderate and High groups, and High and Very High groups proved equivalent ($r = 0.15$). In conclusion, all results corroborate the influence of technology and environmental engagement on hydrogen acceptance, which translates to a positive association. Finally, there is relatively consistency across the four measures in terms of average effect size (r): **H1** = 0.29; **H2** = 0.25; **H3** = 0.27; **H4** = 0.28). The results confirm that the tested parameters yield a moderate to large positive effect on domestic hydrogen acceptance.

7. Discussion

This study developed and applied a novel conceptual framework to examine domestic hydrogen acceptance in the UK, where a strategic decision on the role of hydrogen homes is set for 2026 [20]. Operationalising the proposed framework revealed patterns of consumer heterogeneity, which are partially attributed to a mix of psychological and attitudinal factors related to technology and environmental engagement. While Section 5 demarcated the configuration of domestic hydrogen acceptance and established clear differences among the sampled sub-groups through quantitative analysis, Section 6 validated the analysis through additional statistical tests.

It follows that strategic measures should be implemented to strengthen specific psychological and attitudinal parameters across the UK population in support of the domestic hydrogen transition. In view of the results, it is anticipated that scaling up renewable energy deployment, including community-led projects [194–196], would yield positive 'spillover effects' for domestic hydrogen acceptance [197]. A more direct synergy for encouraging the adoption of hydrogen home appliances may also lie with deepening consumer engagement in smart home technologies [64,198], alongside technology innovation in general.

Relatedly, enabling conditions for the domestic hydrogen transition will rest on increasing awareness around climate change [60], thereby raising the overall level of net-zero consciousness nationwide to support residential decarbonisation. In parallel, specific action plans are needed

Table 11
Summary of pairwise comparisons between consumer sub-groups for domestic hydrogen acceptance.

	Table 4 (N = 992)		Table 5 (N = 992)		Table 9 (N = 1213)		Table 10 (N = 1213)		*Combined* (Tables 4, 5, 9 and 10)	
Group comparison	**Effect size (*r*)**	**Rank**	**Effect size (*r*)**	**Rank**	**Effect size (*r*)**	**Rank**	**Effect size (*r*)**	**Rank**	**Mean effect size (*r*)**	**Mean rank**
BLG–MEG	0.15	3	0.13	2	0.21	4	0.18	3	0.17**	3
BLG–VEG	0.33***	6	0.33***	6	0.39***	6	0.44***	6	0.37***	6
BLG–FSG	0.14	2	0.16	3	0.08	1	0.08	1	0.12**	2
MEG–FSG	0.02	1	0.04	1	0.13	2	0.10	2	0.07*	1
VEG–FSG	0.20	5	0.18	4	0.33***	5	0.38***	5	0.27***	5
MEG–VEG	0.18	4	0.21	5	0.20***	3	0.28	4	0.22**	4

*** Large effective size (>0.26).
**Moderate effective size (0.08–<0.26).
* Small effect size (0.01–<0.08).

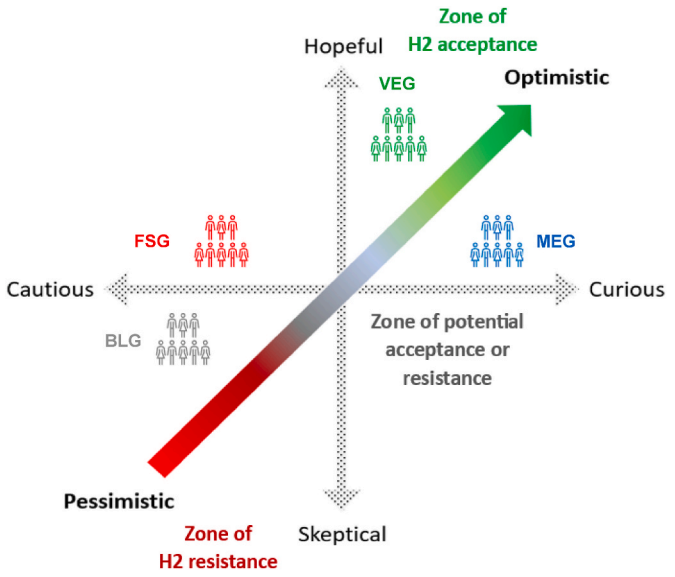

Fig. 11. Location of consumer sub-groups on the hydrogen acceptance matrix.

Table 12
Spearman's rank correlation coefficient results for hypotheses tests.

	Domestic hydrogen acceptance***	Willingness to adopt domestic hydrogen***
Hypothesis	**Spearman's rho** (confidence levels)	**Spearman's rho** (confidence levels)
H1	0.342 (0.290–0.393)	0.287 (0.232–0.339)
H2	0.297 (0.243–0.349)	0.308 (0.255–0.360)
H3	0.306 (0.252–0.357)	0.324 (0.272–0.357)
H4	0.298 (0.244–0.350)	0.306 (0.252–0.357)
Average (rho)	0.311	0.306

*** All correlation results are significant at 1% level (2-tailed).

to increase awareness and knowledge for renewable energy across the general population, as a stimulus for bolstering hydrogen experience, engagement, and acceptance [60,95,199].

Information provision has been highlighted as a critical acceptance factor for consumers in the UK [200,201], Europe [202], Asia [95,203] and Australia [204,205]. Notably, research conducted in Australia [46,205] has flagged the importance of disseminating clear information on the potential costs, benefits, and risks of HETs. In response, UK stakeholders should focus on communicating the prospective economic and environmental benefits of low-carbon hydrogen [206–208], while taking necessary steps to address perceived and actual risk factors [13]. Educational campaigns for domestic hydrogen [28] present a low-hanging, sensitive intervention point for shifting the underlying dynamics [209] and public debate around hydrogen [210] in support of decarbonisation efforts [211]. As van Voss and Rafaty [212] 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 [109,213] of hydrogen home appliances.[10] To date, opportunities for experimentation have been largely restricted to limited project sites, such as the Hydrogen Experience

[10] 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 [143].

Table 13
Pairwise test comparisons for technology and environmental engagement.

(H1) *Interest and engagement with environmental issues such as climate change*

Group comparison	Std. Test statistic	*p*-value	Adjusted *p*-value	Effect size (*r*)
Very Low–Low	2.31	0.021	0.212	0.15**
Very Low–Moderate	5.49	<0.001	<0.001	0.22**
Very Low–High	9.00	<0.001	<0.001	0.44***
Very Low–Very High	8.02	<0.001	<0.001	0.63***
Low–Moderate	3.71	<0.001	0.002	0.14**
Low–High	8.20	<0.001	<0.001	0.37***
Low–Very High	6.89	<0.001	<0.001	0.44***
Moderate–High	6.53	<0.001	<0.001	0.22**
Moderate–Very High	5.11	<0.001	<0.001	0.20**
High–Very High	1.30	0.195	1.000	0.06*

(H2) ***Knowledge and awareness of renewable energy technologies***

Group comparison	**Std. Test statistic**	***p*-value**	**Adjusted *p*-value**	**Effect size (*r*)**
Very Low–Low	1.64	0.102	1.000	0.12**
Very Low–Moderate	4.56	<0.001	<0.001	0.25**
Very Low–High	7.77	<0.001	<0.001	0.43***
Very Low–Very High	8.30	<0.001	<0.001	0.50***
Low–Moderate	3.32	<0.001	0.009	0.18**
Low–High	7.12	<0.001	<0.001	0.31***
Low–Very High	7.66	<0.001	<0.001	0.35***
Moderate–High	5.15	<0.001	<0.001	0.11**
Moderate–Very High	6.12	<0.001	<0.001	0.14**
High–Very High	2.30	0.190	0.192	0.08**

(H3) ***Consumer innovativeness and adoption category***

Group comparison	**Std. Test statistic**	***p*-value**	**Adjusted *p*-value**	**Effect size (*r*)**
Low innovator– Medium innovator	5.25	<0.001	<0.001	0.18**
Low innovator– High innovator	9.94	<0.001	<0.001	0.41***
Medium innovator –High innovator	6.89	<0.001	<0.001	0.22**

(H4) ***Overall level of environmental and technology engagement***

Group comparison	**Std. Test statistic**	***p*-value**	**Adjusted *p*-value**	**Effect size (*r*)**
Very Low–Low	5.273	<0.001	<0.001	0.20**
Very Low–Moderate	8.676	<0.001	<0.001	0.36***
Very Low–High	11.646	<0.001	<0.001	0.51***
Low–Moderate	4.806	<0.001	<0.001	0.15**
Low–High	7.544	<0.001	<0.001	0.30***
Moderate–High	3.504	<0.001	0.003	0.15**

*** Large effective size (>0.26).
**Moderate effective size (0.08–<0.26).
* Small effect size (0.01–<0.08).

Centre in Ellesmere Port, Northwest England [214], which was designed to inform residents about prospective plans for a hydrogen village trial in the area [215,216]. However, the proposition of such trials has been characterised by a degree of controversy, misinformation, and public backlash [217,218], as noted in Section 5.2.2.

Critically, leading academics have also cast doubt over the viability of domestic hydrogen [219], and foremost, a 'blue' hydrogen pathway contingent on steam methane reformation and carbon capture and storage [220,221]. Community resistance to local energy projects is well documented in the energy transitions literature [222–224], reflecting the need for local consent and consumer engagement in communities targeted for hydrogen village trials [20]. Wider efforts to increase observability and trialability across different UK industrial clusters [225] and other locations around the country [226,227] would help legitimise the hydrogen industry's social license to operate [118,228], and likely offset some degree of consumer scepticism and mistrust in energy companies and GDNOs.

The main responsibility for converting fears over domestic hydrogen into hopes [229] lies with the government and energy sector,

particularly during the early stages of the transition. As reflected in the UK Hydrogen Strategy [20], the government has long-term commitments towards realising visions for a national hydrogen economy [28,230]. 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 [174,231,232]. At the same time, the role of the media [233,234], and specifically, the growing power of digital communication platforms [235,236], cannot be overstated in shaping socio-technical imaginaries for the hydrogen economy [13,237,238] and associated narratives around climate change [239,240].

The role of intermediary actors such as industry associations [241] and non-government organisations [242], as well as middle actors such as building professionals [243,244], will further shape the dynamics of trust and acceptance for hydrogen transition [35,36]. 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), carry the responsibility of addressing consumer concerns regarding the performance and safety of hydrogen appliances, while delivering on their promise to make hydrogen boilers price-competitive [138,245]. This study suggests that fuel stress, when controlling for other variables, may influence support for hydrogen homes in a positive direction. Amid the growing fuel poverty crisis [246], it follows that a significant proportion of the population will be staking their support for domestic hydrogen on its prospective financial impacts.

8. Conclusion

By way of conceptual and empirical contribution, this study extends the evidence base on domestic hydrogen acceptance towards a deeper understanding of consumer attitudes, which can be further enriched through subsequent mixed-methods research. Such insights are needed to accentuate hopes for a sustainable domestic hydrogen future, grounded in social fairness and energy justice [247]. 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. Foremost, through mixed-methods data analysis, this study demonstrates the extent to which property owners responsible for investment decisions around cooking and heating technologies may hold divergent preferences and expectations for low-carbon homes [13].

To advance the social science research agenda on the hydrogen economy [31,40], follow-up work can extend the focus to householders within the rental sector, as well as landlords, thereby bridging the knowledge gap between findings from online survey studies [39,165,189] and focus groups [13,43,138,248]. Foremost, visions for a low-carbon domestic hydrogen future [31] will rest on developing a rich understanding of public perceptions [249–251], and moreover, engaging consumers in the transition process [35,46]. Both sides of this equation can be supported by increasing the prevalence of consumer-oriented research [252], which should leverage the benefits of advanced mixed-methods approaches [253].

While comprehensive in its conceptual, methodological, and empirical approach, this study has a few limitations which should be addressed in subsequent studies. Firstly, fuel poor respondents represented in this study were mostly composed of consumers experiencing moderate to high levels of fuel stress (~83.7%). A stricter recruitment process targeting UK households in more extreme levels of fuel poverty would help enrich these provisional findings and substantiate the comparative analysis.

Having demonstrated the applicability of the domestic hydrogen acceptance matrix, subsequent survey studies can apply the framework more directly by eliciting whether respondents self-identify as *hydrogen optimists, hydrogen hopefuls, hydrogen-curious, hydrogen-neutral, hydrogen-cautious, hydrogen sceptics, or hydrogen pessimists.* An additional answer response (i.e. none of the above) should be given for respondents who fail to self-identify with a one-dimensional perspective, thereby enabling opportunities to better establish the propensity for two-dimensional and multi-dimensional perspectives.

Furthermore, explanations regarding the domestic hydrogen acceptance can be given at the start of the question to ensure full comprehension of the task at hand and the response options. This approach would enable the inclusion of a new form of information provision in survey studies on hydrogen acceptance. Alternatively, or in conjunction, survey participants can assess how they self-identify with different positions on the acceptance matrix according to a given Likert scale, thereby establishing more robust quantitative insights on the configuration of attitudes towards hydrogen homes.

Such approaches can help counteract limitations observed in this study related to survey fatigue, disinterest, or other factors, which resulted in one-third of respondents foregoing the opportunity to give a qualitative response, while others only gave brief responses in some cases. Furthermore, this approach would circumvent potential issues arising from the subjective nature of classifying qualitative respondents to respective perspectives. A complementary approach to delve deeper into the multi-dimensionality of consumer perspectives could involve asking respondents to visually pinpoint their position on the hydrogen acceptance matrix (see Fig. 1) or a simplified version of the matrix [36], as a more interactive means of engaging respondents.

While scholarly engagement with domestic hydrogen acceptance remains relatively nascent [35], the emerging evidence base highlights a critical pathway towards achieving social implementation: key stakeholders within the public and private sector should account for the dynamics of consumer heterogeneity when devising strategies to support residential decarbonisation.

In addition to the recommendations previously outlined, longitudinal studies [39,254] are needed to overcome the constraints implicit within a cross-sectional research design [72]. As a starting point, time series data such as the UK government's Public Attitudes Tracker can leverage lessons from this study to support net-zero commitments [255]. Foremost, a more intricate understanding of consumer engagement levels in technology and the environment can be developed to better comprehend the composition of UK society. By fine-tuning the requisite survey instruments, longitudinal data on the psychological and attitudinal parameters underlying this analysis can be leveraged by social scientists. As suggested by this study, such insights may prove critical to optimising segment-specific strategies in support of residential decarbonisation and the growth of national hydrogen economies. Above all, through early recognition of the domestic hydrogen acceptance matrix, net-zero actors can help steer society towards a more optimistic and equitable energy future, which internalises reflective consumer engagement and deliberative policy making.

Data availability statement

Data underlying this study can be accessed through the Cranfield University Online Research Data (CORD) Repository at: 10.17862/cranfield.rd.23585091.

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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.

Acknowledgments

This research was supported by the Engineering and Physical Sciences Research Council (EPSRC) Grant EP/T518104/1, and sponsored by Cadent Gas Ltd.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.02.247.

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2024-03-22
Elsevier
https://doi.org/10.1016/j.ijhydene.2024.02.247
Gordon JA, Balta-Ozkan N, Nabavi SA. (2024) Hopes and fears for a sustainable energy future: enter the hydrogen acceptance matrix. International Journal of Hydrogen Energy, Volume 60, March 2024, pp. 1170-1191

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