

Necessary and sufficient conditions for deploying hydrogen homes: A consumer-oriented perspective

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ARTICLE INFO

Handling Editor: Prof. J. W. Sheffield

Keywords:

Hydrogen transition
Residential decarbonisation
Technology adoption
Social acceptance
Necessary condition analysis
Combined importance-performance map analysis

ABSTRACT

As part of its efforts to secure a 'net-zero society', the UK government will take a strategic decision on the role of hydrogen in decarbonising homes within the next years. While scholars have recently advanced the social science research agenda on hydrogen technology acceptance, studies are yet to engage with the prospective dynamics of adopting 'hydrogen homes'. In response, this study examines the perceived adoption potential of hydrogen heating and cooking technologies, as evaluated through the eyes of consumer. Engaging with behavioural and market acceptance, this research draws on data from a broadly nationally representative online survey to examine the influence of safety, technological, economic, environmental, and emotional factors on the domestic hydrogen transition in the UK context. The analysis follows a multi-stage empirical approach, integrating findings from partial least squares structural equation and necessary condition analysis to crystallise insights on this emergent subject. At this juncture, perceived adoption potential may hinge primarily on emotional, environmental, safety, and to a lesser extent, technological perspectives. However, consumers have an expressed preference for hydrogen heating over hydrogen cooking, with perceived boiler performance emerging as a necessary condition for enabling adoption potential. At the formative phase of the transition, risks associated with energy insecurity and fuel poverty exceed concerns over purchasing and running costs. Nevertheless, economic factors remain less critical during the pre-deployment phase of the innovation-decision process. Across the full sample, simple slope analysis highlights the moderating effects of gender, age, and housing tenure. Moreover, statistically significant differences from both a sufficiency- and necessity-based perspective are detected between male property owners aged 55+ and female mortgage owners 18–34 years old. By bridging the knowledge gap between social acceptance and adoption intention, this contribution reinforces the need for consumer engagement in the hydrogen economy, advocating for more fine-grained, mixed-methods analyses of technology acceptance dynamics to support decarbonisation strategies.

1. Introduction

As an emerging energy vector with substantial potential for supporting large-scale multi-sectoral decarbonisation [1,2], hydrogen has become a focal point of the energy transition [3,4].¹ This trajectory is strongly reflected by the growth of national policies in many of the world's leading economies [5,6]. Hydrogen is particularly attractive to energy import-dependent nations such as South Korea [7] and Japan [8], while resource-rich countries including Australia, New Zealand, and

Chile are seeking to capitalise on export opportunities [5,9]. Contingent on the dynamics of emerging geo-economic competition, hydrogen could foreseeably reshape future geo-political relations [5,10].²

Globally, hydrogen and hydrogen-based fuels are forecasted to play a critical supporting role in decarbonising hard-to-abate sectors [11,12], foremost heavy industry [13,14] and heavy-duty transport [15,16]. However, at the national level, the move towards a 'hydrogen economy' [17,18] could also help accelerate residential decarbonisation in countries with large-scale natural gas infrastructure [19], such as Germany [20,21], the Netherlands [22,23], and the United Kingdom (UK) [24,

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¹ In the Sustainable Development Scenario proposed by the IEA [11], hydrogen accounts for 13% of final energy demand, with global production increasing seven-fold to 520 Mt.

² Notably, the International Energy Agency (IEA) suggest global hydrogen trade in a 1.5 °C scenario may consolidate "a more diversified and competitive energy market" by facilitating new trade relationships between countries" [367].

Nomenclature		LV	Latent variable
ARENA	Australian Renewable Energy Agency	MGA	Multigroup analysis
BEIS	Department for Business, Energy & Industrial Strategy	Mt	Metric tonnes
BLR	Perceived Boiler Performance	MtCO ₂ e	Metric tonnes of carbon dioxide emissions
CA	Cronbach Alpha	NCA	Necessary condition analysis
CAGR	Compound annual growth rate	NGN	Northern Gas Networks
CB-SEM	Covariance-based structural equation modelling	PAP	Perceived Adoption Potential
CCC	Committee on Climate Change	PAT	Public Attitudes Tracker
CCS	Carbon capture and storage	PLS-MGA	Partial least squares multigroup analysis
CE-FDH	Ceiling-envelopment free disposal hull	PLS-SEM	Partial least squares structural equational modelling
CMB	Common Method Bias	PP	Production Perceptions
CR	Composite reliability	PSC	Perceived Socio-economic Costs
CR-FDH	Ceiling-regression free disposal hull	RD&D	Research Development and Demonstration
CUTE	Clean Urban Transport for Europe	R ²	Coefficient of determination
EC	European Commission	SEM	Structural equation modelling
FP	Financial Perceptions	SLO	Social license to operate
HET	Hydrogen energy technology	SMR	Steam methane reformation
HFCVs	Hydrogen fuel cell vehicles	SP	Safety Perceptions
HFSs	Hydrogen fuelling stations	TAM	Technology Acceptance Model
HOB	Perceived Hob Performance	TP	Technology Perceptions
IA	Indicator average	UK	United Kingdom
IEA	International Energy Agency	UTUAT	Unified Theory of Acceptance and Use of Technology
LM	Linear model	VIF	Variance inflation factor

25].

This empirical study focuses on the UK, which persists as a laggard in electrifying and insulating its national housing stock [26–28]. At present, 84% of domestic properties remain connected to the gas grid [29, 30], whereas four million are located off-grid and reliant on alternative fuels for heating and cooking [31]. In 2020, the residential sector was responsible for around 16% of total UK greenhouse gas (GHG) emissions, with carbon dioxide accounting for 97% of the total [32].³ With around 21.2 million gas boilers installed across the UK housing stock [29,33], fuel combustion for heating accounted for 14% of emissions [32]. Additionally, around 12.7 million gas hobs are in use [29,33], which contribute to approximately 2% of national emissions [32].

Consequently, converting the gas grid to supply parts of the housing stock with low-carbon hydrogen [34–36] may prove critical to supporting net-zero ambitions [37–39].⁴ In response, the UK Heat and Buildings Strategy [40] aims to reduce emissions from the buildings sector to less than 2 MtCO₂e by 2050, which will require phasing out the installation of natural gas boilers by 2035. However, scarce attention has focused on the parallel challenge of mitigating emissions from residential cooking [41].

The UK government is set to take a strategic decision on the role of domestic hydrogen – consisting of hydrogen-fuelled technologies for space heating, hot water, and cooking [42] – by 2026 [43]. Policy making will rest on evidence from research, development, and demonstration (RD&D) activities across the North of England [44] such as the HyDeploy project [45] and prospective opportunities for local hydrogen trials across parts of the UK [43,46] including Fife in east-central Scotland [47,48]. Supporting this trajectory, the £12 million FutureGrid project led by National Gas is testing the feasibility of converting the gas

grid to hydrogen [49,50].

Achieving large-scale residential decarbonisation in the UK and improved energy security [43,51] will call for a “multi-pronged policy framework” [52] to support “rapid and transformational societal change” [53]. A combination of stringent policies and easy-to-deploy, non-disruptive technologies [28] will be required to support consumer expectations for making homes “clean, safe, warm, and smart” [41]. However, low-carbon technologies such as heat pumps and district heating continue to face several technology diffusion and policy barriers, which have offset market penetration in the UK [28,54–56].

One of principle barriers to decarbonising homes is a lack of social acceptance [57,58], which has been linked to a deficit in energy literacy [59], as reflected by limited consumer knowledge and awareness of hydrogen technologies at this point in time (see Section 6.1.1). In July 2023, local opposition in Whitby village (Ellesmere Port) reached a tipping point [60,61], leading to the cancellation of a planned hydrogen trial for the area [62],⁵ which cost £8.28 million during the design phase alone [63].⁶ The rise of consumer resistance in Whitby has cast significant uncertainty over the socio-political legitimacy of hydrogen homes [64], culminating in the subsequent cancellation of a trial for Redcar in Yorkshire⁷ [65,66].

Reflecting the context of this analysis, Quarton et al. [67] argue for a more fine-grained representation of consumer perceptions when considering the proposition of injecting hydrogen into existing natural gas grids:

“The uptake of new technologies is not only driven by cost or efficiency-based metrics for the entire energy system, but also by consumer choice, dependent on social factors and personal preference” [67].

³ Garden machinery, and fluorinated gases released from aerosols and metered dose inhalers also contribute to GHG emissions [32].

⁴ In the words of Parra and colleagues [368]: “Hydrogen technologies can play an important role in decarbonising our energy system in a variety of ways across the energy value chain. It is therefore critical to identify the strategic roles as well as the conditions under which hydrogen energy systems become attractive for the energy transition.”

⁵ The cancellation was made effective by Energy Minister, Lord Callanan in July 2023 [369].

⁶ 60% of the costs had been met by the gas distribution network operator, Cadent [63].

⁷ Northern Gas Networks (NGN) contributed around 10% to the £6.64 million design phase of the Redcar trial in Yorkshire [63], which was cancelled in December 2023.

Increasingly, researchers are developing new frameworks and approaches to examine the social acceptance of renewable energy technologies [68–70], reflecting the notion that positive consumer engagement is a “prerequisite for the adoption and introduction of new technologies” [71] such as hydrogen boilers and hobs [42,72].

Drawing on online survey data collected at the end of 2022 ($N = 1845$), this analysis advances the social science research agenda on hydrogen acceptance [73,74] by adding to the limited number of nationally representative studies on hydrogen homes [73,75,76]. Specifically, this study develops a consumer-orientated conceptual framework to examine the perceived adoption potential of hydrogen homes in the UK context. By advancing scientific knowledge on the perceptual and emotional antecedents of adoption potential, including the nature and intensity of observed relationships, this research aims to bridge a critical knowledge gap between social acceptance and potential behavioural acceptance [77]. The objective is supported by evaluating the extent to which the safety, technological, economic, environmental, and emotional perspectives may shape consumer attitudes toward the domestic hydrogen transition, which is simplified via the acronym ‘STEEEP’.

Operationalising the STEEEP Framework, the purpose of this study is to evaluate the critical success and resistance factors influencing perceived adoption potential for hydrogen boilers and hobs, as investigated across the UK population and specific consumer segments. In view of the policy dynamics underlying hydrogen homes in the UK [43,78] and burgeoning level of financial investment in hydrogen energy technologies around the globe [79,80], a consumer-oriented evidence base is critical for pre-empting the risk of a socially-rejected pathway for residential decarbonisation.

To evaluate the components of the STEEEP Framework (and an adapted version of the framework) in terms of sufficiency- and necessity-based logic, this study combines partial least squares structural equation modelling (PLS-SEM) [81,82] with necessary condition analysis (NCA) [83,84], which is supplemented by multigroup analysis [85,86] and combined importance-performance map analysis (cIMP) [87]. This configuration advances an innovative mixed-methods approach, as espoused by Richter et al. [84,87] and advocated for by Kurtaliqi and colleagues [88] to enhance quantitative insights from PLS-SEM. Overall, the research focus supports the UK government’s intention to develop consumer engagement in the emerging hydrogen economy [43].

Following this introduction, Section 2 provides an overview of developments in social science research on hydrogen acceptance. Next, Section 3 describes the methodological approach as a way of introducing PLS-SEM and NCA, alongside importance-performance map analysis (IMP) and cIMP. Subsequently, Section 4 draws on supporting literature to generate hypotheses regarding the dynamics of domestic hydrogen adoption potential from both a sufficiency- and necessity-oriented perspective. Section 5 outlines the conceptual approach and develops the STEEEP Framework, while Section 6 reports the results. Next, Section 7 discusses the practical, theoretical, and methodological implications of the findings, while reflecting on the future research agenda. Section 8 summarises the key findings and draws conclusions.

2. Social science research on hydrogen acceptance

Social acceptance refers to a multi-actor [89] and multi-level process [90], which is characterised by complex and dynamic interactions [91], occurring across multiple scales or levels [90]. For example, Cherry et al. [92] recognise the relevance of multiple factors such as trustworthiness, fairness, affordability, convenience, and safety in strengthening public acceptance for strategies supporting the development of resource-efficient products. Although the evidence base remains limited, recent findings suggest multiple dimensions will also influence the potential for domestic hydrogen adoption [44,75], including perceived risks, costs and benefits, and technology perceptions [77].

Hydrogen energy technology (HET) acceptance has been examined

over the course of two decades [93,94], initially motivated by interest in the deployment of hydrogen fuel cell vehicles (HFCVs) [95,96], hydrogen (fuel cell) buses [97,98], and related infrastructure such as hydrogen fuelling stations (HFSs) [99,100].⁸ Flagging the historical importance of social acceptance, Raven et al. [101] described the London Clean Urban Transport for Europe (CUTE)⁹ hydrogen project as “encountering significant discontent in the earlier stages of engagement.” Reflecting the potential for public resistance, O’Garra et al. [102] found that only one-third of survey respondents ($N = 420$) were clearly in favour of hydrogen buses prior to their introduction.

Furthermore, the London case study highlights the importance of raising public awareness to support technology acceptance [102], whereby respondents cited an explicit preference for more information [99].¹⁰ Early experiences from the CUTE project and similar hydrogen trials [96] provide valuable insights and lessons for supporting a socially acceptable transition to other emerging energy technologies [103],¹¹ such as hydrogen boiler and hobs [41].

Following an initial wave of research activities associated with projects such as CUTE, acceptance studies on the use of hydrogen for transport have steadily increased [104,105]. As a result, the literature on hydrogen for transport applications is comprehensive [95,106] and international in scope, extending to India [107], Japan [108], South Korea [109], Malaysia [110], and China [111], in addition to countries in the Global North [96,112–114]. By contrast, scholarly interest in hydrogen homes is a more recent development [115], with the first social acceptance study dating back to 2017 [116]. As an emergent research area, studies on domestic hydrogen acceptance remain limited primarily to the UK [73,117], Australia [75,115], and parts of Europe [118,119].

In the context of developing national hydrogen economies, a “new social science research agenda” is needed to account for the dynamics of social acceptance [73]. At present, the literature is characterised by an underlying deficit in terms of theoretical and empirical engagement [94, 120]. Notably, in the early 2010s, Huijts [121] critiqued the inconsistent use of terminology within the hydrogen acceptance literature, while highlighting a tendency towards representing psychological variables with a single measurement item, which undermines reliability and validity in quantitative analyses. More recently, Scovell [94] further underscored inconsistencies regarding the measurement of psychological constructs, alongside a lack of clarity regarding how “context-specific beliefs” shape consumer attitudes towards hydrogen energy technologies.

In response, this study is motivated by the need to advance scholarly understanding of adoption prospects for hydrogen boilers and hobs, recognising that cross-sectoral synergies are critical to supporting the hydrogen economy [3]. Moreover, consumer perspectives should be factored into policy making at an early stage of the prospective transition to hydrogen homes, as a critical mechanism for pre-empting social resistance and setbacks in low-carbon energy policy [122–124]. For example, Cohen et al. [122] note how social resistance “has the potential to slow the progress of new developments, and derail national goals of energy supply security and greenhouse gas reduction.” In this sense, results from this analysis are partially retrospective of recent events in the North of England, but moreover, prospective of the adoption dynamics underlying hydrogen heating and cooking technologies.

⁸ Dating back to the early 2000s, fuel and auto companies were already investing between \$500 million and \$1 billion annually in HETs [370].

⁹ In December 2001 the European Commission (EC) awarded €18.5 million to nine cities ([371], including London [372,373], to trial hydrogen buses [374, 375].

¹⁰ Specifically, 59% of survey respondents ($N = 346$) cited the need for more information to strengthen support for local HFSs.

¹¹ Emmerich [103] discusses HFSs, battery storage, and biofuel production plants in the German context.

Accordingly, this research provides insights on the innovation-decision process [125,126] of domestic hydrogen during the formative phase of technology diffusion [127], as reflected in Fig. 1. As hydrogen homes are yet to be commercialised and deployed [77], this analysis reflects the interplay between two stages; the ‘knowledge stage’ where consumers become aware of the technology, and the ‘persuasion stage’ where initial attitudes are formed in view of perceived risks, costs, benefits, and associated factors, ahead of the ‘decision stage’ (i.e. adoption or rejection) [126]. The inclusion of perceived adoption potential as an interim measure within the innovation-decision process can help bridge understanding on the intention-behaviour gap [43,128,129] for hydrogen energy technologies.

3. Material and methods

3.1. Survey design and data collection

This quantitative study employed an online survey to gather empirical data on public perceptions of hydrogen homes in the UK. The survey instruments were developed through a combination of qualitative findings, extracted primarily via literature review [44,77] and online focus groups (February–April 2022) [41,130,131]. Drawing on inputs from technical experts and social scientists, the questionnaire items were refined ahead of a series of pilot tests. The survey was programmed in Qualtrics [132] and validated for content and face validity during the testing phase, ahead of deployment in October 2022. Details of the survey items, answers scales, and supporting literature are provided in Appendix A (see Supplementary Note 1).

To help offset survey bias, in addition to minimising drop-out rate due to potential disinterest or fatigue [133,134],¹² a series of information provision materials were included [135]. Specifically, participants were provided with information on hydrogen production methods in the context of the twin-track strategy, hydrogen-related activities in the UK context, and specific details concerning hydrogen boilers and hobs (see Appendix B). The selection was based on the use of information provision materials in prior research [41,136–138] and informed by recent policy documents [43,51].

Factual and inherently neutral information was selected to support the analysis, as opposed to testing the effects of positive or negative framing [139,140], or scenarios [8,141], which can support the future research agenda. Nevertheless, the introduction of targeted and objective information is likely to influence respondents’ subjective views about hydrogen [75], which could not be directly examined due to the lack of a control group. Implications regarding the limited baseline knowledge of hydrogen fuel and the use of information provision materials and are further discussed in Section 8.

3.2. Sample characteristics

The sample included property owners living in homes with a natural gas boiler and hob. Additionally, all respondents expressed at least moderate levels of financial involvement in decisions related to natural gas appliances, while attributing at least moderate importance to choosing between technologies, as reported in Supplementary Note 2 (see SN2).¹³ Applying these filters helps account for the influence of agency and choice regarding attitudes towards hydrogen homes, which are seldom factored into studies on energy acceptance [142,143]. The selection was based on the rationale that decisions regarding hydrogen homes may prove most pertinent to this demographic group [144]. However, outright property owners were significantly underrepresented

(–19.9%) compared to mortgage owners.

As highlighted in various scientific disciplines [145–147], nationally representative survey data can help support the generalisability of empirical findings through a more reliable estimation of population wide patterns. This study implemented quotas for the gender, age, location, housing tenure, and property type to help increase the representativeness of the final sample (N = 1845).

The sample proved highly nationally representative in terms of location (see SN3), with partial overrepresentation from female respondents (+4.9%), while the oldest age group was underrepresented (–11.5%), as documented in Table 1. Additionally, in terms of property type, the sample underrepresents consumers living in a flat, apartment, or bungalow (–17.7%). However, this disparity is potentially less relevant since gas-based heating and cooking are more prevalent across detached houses (+11.1%), semi-detached houses (+13.5%), and terraced houses (–6.8%) [148].

In sum, the sample is relatively balanced in terms of gender, skewed towards a younger demographic, broadly nationally representative of UK regions but primarily composed of suburban or urban households (73.7%),¹⁴ while overrepresenting mortgage owners and residents of detached and semi-detached homes.¹⁵ Additional details supporting the breakdown reported in Table 1 are provided in SN3.

The sampling approach further accounted for socio-structural differences through an embedded multigroup composition (see SN4), which targeted different levels of technology and environmental engagement, in addition to socio-economic conditions. Specifically, one of the four sub-groups comprised respondents experiencing fuel poverty or high levels of fuel stress, while being less than moderately engaged in technology and the environment (N = 379). Accordingly, the sample composition is unique in capturing a configuration of consumers, which could foreseeably shape the early adoption dynamics of hydrogen homes.

3.2.1. Gender dynamics and multigroup characteristics

Given the described characteristics of the sample, modelling results are likely to prove relatively generalisable to the population. Nevertheless, a more stringent approach is to reexamine the sample composition through a meaningful filter such as gender: Male: N = 810; Female: N = 1035. Across both segments, there are similar levels of representation regarding the number of occupants per property (single-occupied: Male = 11.6%, Female = 8.8%; two-person: Male = 30.9%, Female = 29.7%; multi-occupancy (3+): Male = 57.5%, Female = 61.5%). Among the male sub-group, outright property and mortgage owners are equally balanced, while age groups are closely split (see Fig. 2a). However, the female sub-group is composed primarily of mortgage owners (72.2%) and less representative of respondents aged 55 or over (18.1%).

Mirroring these dynamics, in comparative terms, the female sub-group is overrepresented by respondents in the lowest income bracket (<£23,500) but underrepresented within the top income bracket (>£62,500), as illustrated in Fig. 2b (see SN5). Such intricacies regarding sample characteristics are critical to acknowledge at the outset and motivate the need for examining moderating variables [149–151], in addition to performing contrast analysis [152] and where viable multigroup analyses [86,153].

This study internalises the above observations to leverage the opportunity for comparing sub-samples, as undertaken for the respective consumer sub-groups (MEG, VEG, FSG, BLG) in parallel research [154]. The larger sub-group consists of female mortgage owners aged 18–34 (N = 282). By contrast, the smaller sub-group is composed of male property

¹² Responses were excluded when deemed unsuitable due to a fast completion time (i.e. less than 8 min).

¹³ Measured using a five-point Likert scale where the moderate response represented the mid-point.

¹⁴ Respondents from rural areas accounted for 17.4% of the sample.

¹⁵ Additionally, socio-demographic information was recorded for income, education level, and number of occupants per household, without applying specific quotas (see SN3).

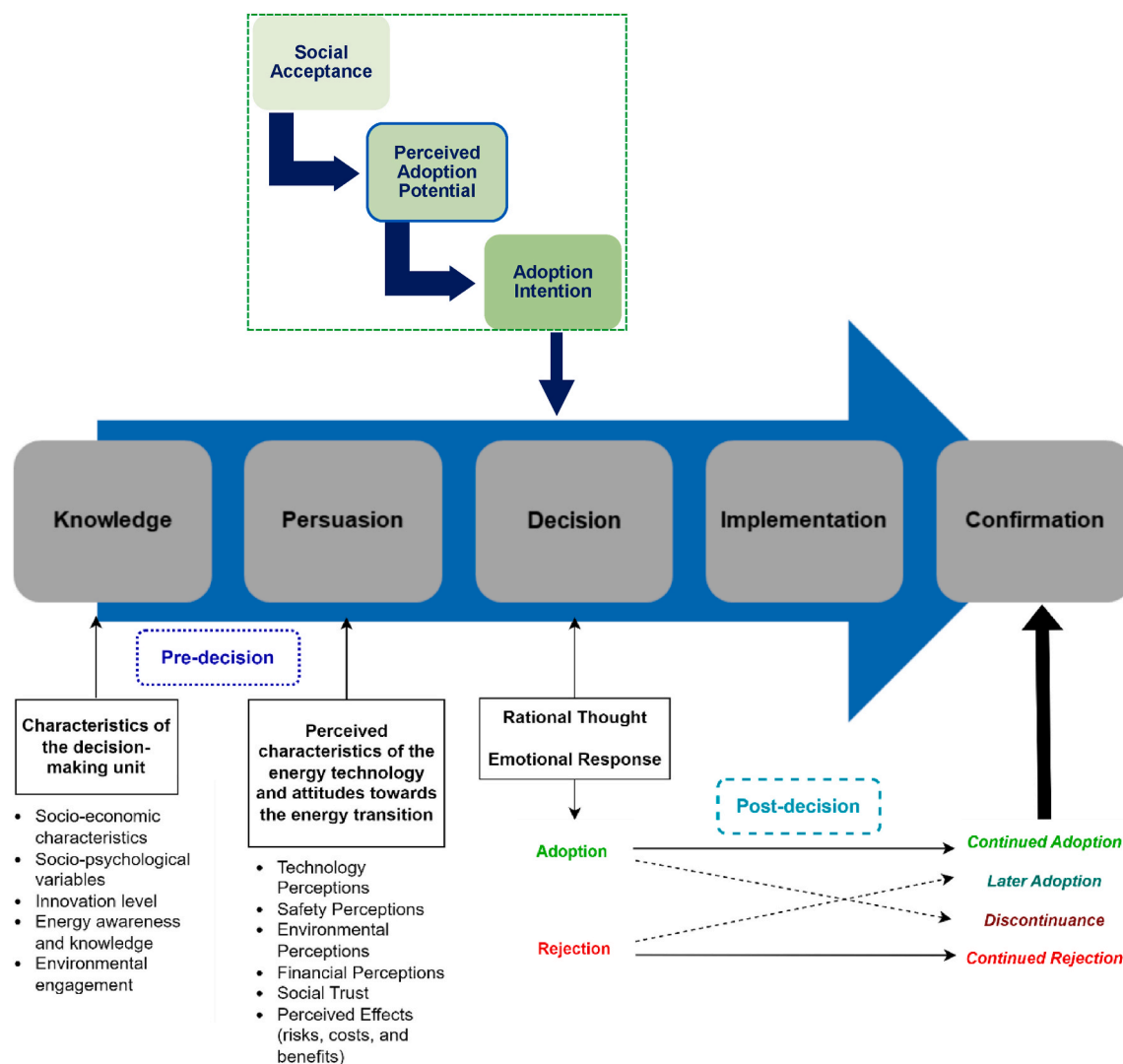


Fig. 1. Innovation decision-process for domestic hydrogen acceptance and adoption based on Rogers' Diffusion of Innovation Theory [125] and the unified theory of domestic hydrogen acceptance [77].

owners aged 55 and over ($N = 160$), thereby yielding diametric segments. Annual income level was also investigated as a potential filter but excluded due to sample size constraints.

At the overall sub-sample level ($N = 442$), representation is similar for properties with two dwellers (42.8%) and three or more inhabitants (48.4%), while single-person homes are least represented (8.8%). However, among the male sub-group, there is a higher proportion of respondents from single-occupied homes (15.6%) compared to female respondents (5.0%). Moreover, two-person households feature predominantly for the male segment (56.9%), whereas multi-occupancy homes (3+) account for 60% of the female segment. These dynamics should be borne in mind throughout the multigroup analysis (see Section 6.5), since a family-oriented perspective is more embedded within the female demographic composing this specific sample of UK consumers, as further reflected upon in Section 7.

Fig. 3a demonstrates relative levels of equilibrium between the two sub-groups according to annual income level, although the male sub-sample retains a higher representation in the top income bracket. In conjunction, a degree of equivalence in this regard is reflected by similar levels of fuel stress representation, as shown in Fig. 3b. However, it also emerges that the male sub-group is composed of respondents with higher levels of technology and environmental engagement, whereas 50% of the female sub-group is composed of respondents belonging to

the Baseline Group (BLG).¹⁶

3.3. Statistical analyses

3.3.1. Partial least squares structural equation modelling

This analysis employs partial least squares structural equation modelling (PLS-SEM) [69,70] to evaluate the dynamics of perceived adoption potential for hydrogen homes. PLS-SEM has been increasingly applied by social scientists to conduct exploratory research [155,156] across a wide range of interest areas [81,86]. Recent coverage includes smart energy technology adoption [157,158], adoption of solar power and biofuels [159], climate change awareness among farmers [160], energy management and environmental performance [161], and adoption of green information technology [162]. PLS-SEM has also been leveraged to explore public perceptions of hydrogen refuelling stations in South Korea [163] and more recently, HFCVs in India [164,165]. The

¹⁶ i.e. Not fuel stressed and with less than moderate levels of technology and environmental engagement.

Table 1
Socio-structural and socio-demographic characteristics.

Socio-demographic variable	Full sample (%) (N = 1845)	UK population (%)	Difference (%)
Age ^a			
18–34	35.5	32.6	+2.9
35–54	39.2	30.6	+8.6
55+	25.3	36.8	–11.5
Gender			
Male	43.9	48.8	–4.9
Female	56.1	51.2	+4.9
Housing tenure			
Property owned outright	37.2	57.1	–19.9
Property owned with mortgage	62.8	42.9	+19.9
Housing type			
Flat, apartment or bungalow	12.3	30.0	–17.7
Detached house	29.1	18.0	+11.1
Semi-detached house	38.5	25.0	+13.5
Terraced house	20.2	27.0	–6.8
Location			
Southwest England and Wales	12.5	13.4	–0.9
Midlands and East of England	25.7	26.2	–0.5
Southeast and London	27.5	27.2	+0.3
North of England and Scotland	34.2	33.0	+1.2

^a Citizens aged below 18 are excluded from the percentage calculations at the national level to support a direct comparison to the sample.

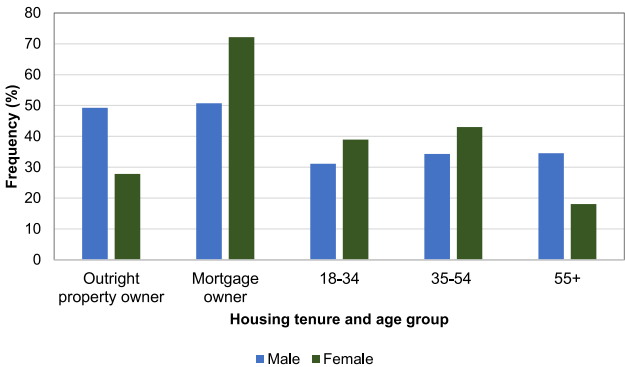


Fig. 2a. Sample composition by gender for housing tenure and age group (N = 1845).

method is recommended when testing emerging technology cases such as hydrogen homes, which entails a focus on theory development and prediction [166].¹⁷

Reflecting the nascency of the topic [19] and lack of rigorous quantitative assessments [94], this study employs PLS-SEM [81,82] to validate the antecedents of perceived adoption potential for hydrogen homes. SmartPLS 4.1 software [167] is employed to examine the predictive capabilities [168] of a newly developed model, which evaluates the behavioural intentions of natural gas users regarding the prospective switch to hydrogen heating and cooking technologies. The two-stage approach is implemented, which involves assessing the measurement

¹⁷ When models and hypotheses have been thoroughly developed, covariance based structural equation modelling (CB-SEM) is the recommended approach for theory testing and confirmation [376]. The notable discrepancies between CB-SEM and PLS-SEM are well-documented in the literature and remain an ongoing area of rich scholarly debate [156,377].

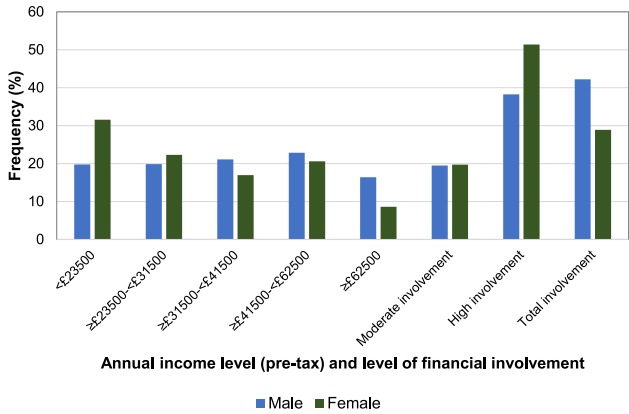


Fig. 2b. Sample composition by annual income level of level of financial involvement for purchasing heating and cooking technologies (N = 1845).

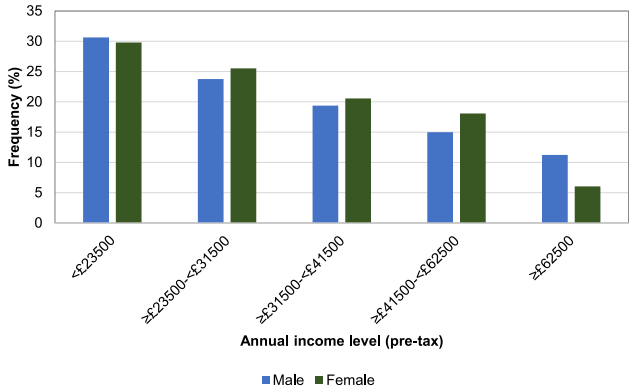


Fig. 3a. Sub-sample composition by annual income level of level (N = 442).

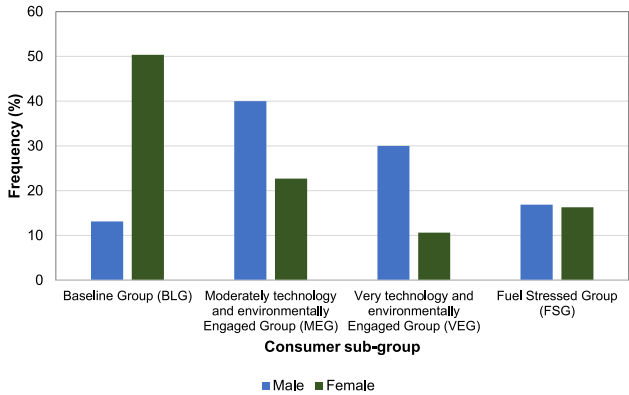


Fig. 3b. Sub-sample composition by consumer sub-groups (N = 442).

model and evaluating the structural model, respectively [82]. To ensure methodological rigour is achieved, researchers should follow best practices when justifying the use of PLS-SEM [169], which includes validity checks for sample size requirements, common method bias (CMB),¹⁸ skewness, and kurtosis [170,171]. Additional technical details

¹⁸ Measurement methods such as questionnaire structure or instructions, or external influencing factors like social desirability response, can introduce elements of bias to result patterns [378].

regarding the implementation of PLS-SEM are described in SN10.

3.3.2. Sample size requirements and preliminary validity checks

Firstly, sample size requirements were verified using model-specific estimates [172]. With seven constructs including one mediator (technology perceptions) and a sole endogenous construct (perceived adoption potential), a sample size of 1091 is needed to detect a small effect size $f^2 = 0.02$ at a 95% significance level ($p < 0.05$), as indicated by G-Power software analysis [173,174]. Consequently, this study met requirements for ensuring statistical power (see SN6). Secondly, CMB was ruled out, since Harman's single factor test [175] returned an overall variance of 29.5%, well below the threshold of 50% (see SN7).¹⁹ Thirdly, normality was assessed via tests for skewness and kurtosis tests [176,177], which returned values within the recommended threshold of ± 1 (see SN8). Overall, the preliminary assessment confirmed the integrity of the data and the suitability of applying PLS-SEM (see SN9).

3.3.3. Importance-performance map analysis

Following the evaluation of the structural model, an importance-performance map analysis (IMPA) is undertaken to support strategic insights on the adoption dynamics of hydrogen homes. IMPA serves as a decision-making tool [178,179] by identifying constructs of strategic value [180,181], which can be targeted by decision makers to support an objective [182,183], such as increasing domestic hydrogen acceptance [33]. The analysis is visualised by plotting unstandardised total effects on the x-axis against latent variables scores rescaled to 0–100 on the y-axis to compare importance and performance [180]. Within the matrix, constructs positioned at the bottom right quadrant are representative of high importance but low performance, which signifies substantial scope for leveraging strategic action [76,184]. Following recent applications from sustainability scholars [183,185], this study follows the guidelines established by Ringle and Sarstedt [180] to carry out an IMPA in Section 6.4.

3.3.4. Simple slopes analysis and multigroup analysis

Accounting for the potential effects of moderating variables is an important component of behavioural research and theory-building [149,186], as reflected by the inclusion of gender, age, experience, and voluntariness in the Unified Theory of Use and Acceptance of Technology (UTAUT) [187]. Moderation occurs when a third construct influences the nature (i.e. magnitude and/or direction) of the relationship between a focal predictor and an endogenous construct [186,188,189].²⁰

While gender and age are typically tested as moderators [190], this study leverages the additional opportunity to operationalise housing tenure status (i.e. outright property owners vs mortgage property owners) as a context-specific categorical moderator, thereby examining consumer heterogeneity within the dataset [191,192]. In doing so, the full sample is split into a sub-sample composed of male property owners aged 55 and over ($N = 160$), and female mortgage owners 18–35 years old ($N = 282$), as described in Section 3.2.1.

Given the discrepancy between sample sizes for the sub-groups, the required conditions²¹ to support a statistical comparison of structural path coefficients via partial least squares multigroup analysis (PLS-MGA) could not be fully established [85,86]. Nevertheless, comparative

insights from descriptive multigroup analysis and necessary condition analysis are presented as supporting evidence, which is also a valid approach given the larger sub-sample size ($N = 442$) and robustness of the measurement model.

Critically, guidelines in the literature emphasise that moderating effects should be evaluated via tests for statistical significance in conjunction with simple slopes analysis, while proposed hypotheses should be grounded in theory and logic [149,189,191,193] as supported in Section 4.8. In response, the independent Mann-Whitney U test [194] is employed to test for statistically significant differences between sub-groups for each construct composing the STEEP Framework (see SN11). In addition to reporting adjusted p -values using the Bonferroni correction [195], effect sizes (r) are calculated by dividing the standardised test statistic (Z) by the square root of the sample ($\sqrt{n}$). The following cut-offs correspond to a small, moderate, and large effect size, respectively: $0.01 < 0.08$; $0.08 < 0.26$; > 0.26 [196–198].

3.3.5. Necessary condition analysis

In 2000, Braumoeller et al. [199] advanced early engagement with the methodology of necessary conditions to address “the gap between theory and empirical testing in political science.” The contribution helped lay the groundwork for increasing the prevalence of necessary condition hypothesising in the social sciences [199]. A decade later, Dul and colleagues [200] outlined two stepwise methodological approaches for developing and testing necessary condition hypotheses in the context of operation management studies. Subsequently, in recognition of the limitations of traditional statistical methods,²² Dul [83] formalised necessary condition analysis (NCA) to better identify the prerequisite factors for achieving a target outcome.²³

Whereas methods such as correlation, multiple regression, and structural equation modelling (SEM) examine sufficiency-based logic (i.e. more of X leads to more of Y),²⁴ NCA identifies whether the existence of a specific factor is required and what level is needed to produce the target outcome [83,201].²⁵ It follows that the ‘necessary condition’ enables the outcome when present but constrains it when absent [202], while other determinants cannot compensate for this absence [83]. Thus, the purpose of NCA is to examine the influence of ‘necessary-but-not-sufficient’ determinants [83,203]. In sum, NCA provides an analytical tool to identify the presence of a factor corresponding to a ‘bottleneck’ (i.e. barrier, obstacle, or constraint) that must be successfully managed to support the feasibility of a target outcome [83].

NCA functions by drawing a ceiling line on top of the data in an XY scatter plot, which demarcates the area with and without observations, thereby generating a potential empty space in the upper left of the plot [83,202]. Two default ceiling lines are available, the ceiling envelopment-free disposal hull (CE-FDH)²⁶ and the ceiling regression-free disposal Hull (CR-FDH)²⁷ [83]. The CE-FDH is recommended when X or Y are discrete with few levels or when the pattern of points around the border is irregular [83,202]. Alternatively, the CR-FDH is appropriate

²² For example, Karwowski and colleagues [206] argue that “correlation, regression, segmented regression, or even latent variable analysis are not fit to test whether or not one construct may be seen as a necessary condition of another.”

²³ As originally discussed in the operations management literature [346], where factors such as resources and employee efforts may enable improved company performance [83].

²⁴ Otherwise referred to as additive average effect logic [205].

²⁵ i.e. the presence of a specific determinant does not automatically produce the target outcome, since a sufficient level of the determinant must also be present [203].

²⁶ As the default non-parametric option, the CE-FDH displays a non-decreasing step function ceiling line (i.e. a piecewise linear function along the upper left observations).

²⁷ The CR-FDH generates an ordinal least squares regression line through the corners of the CE-FDH [83].

¹⁹ An additional measure for evaluating CMB [379] involves generating a random variable to function as the (sole) endogenous construct within the model [380]. Applying this method, all VIF scores for the structural model fell below the threshold of 3.0 [379], suggesting no issue of CMB.

²⁰ For example, Alkaws et al. [381] examined the moderating role of personal innovativeness and user experience in predicting smart meter acceptance among Malaysians ($N = 318$).

²¹ i.e. at least partial measurement invariance in addition to configural invariance.

when X or Y are continuous or when the pattern near the border is close to linear [83,202], as is applicable in this study since ceiling line accuracy values also exceeded 95% [201] (see Section 6.6).²⁸

Although NCA can be performed with both default ceiling lines in SmartPLS 4.1 as a means for testing the robustness of each result [84], Dul and colleagues [204] specify that researchers should only report the selected technique. As a selective and illustrative case, this study employs the CE-FDH to examine the relationship between technology perceptions and its lower-order constructs (i.e. perceived boiler and hob performance),²⁹ as reported in Section 6.6.1.

Once the suitable ceiling line technique is applied, the presence of an empty space in the upper left area of the scatter plot indicates that high levels of the target outcome are not feasible with low values of a predictor [83,202]. The observation implies that X constrains Y,³⁰ with a larger empty space suggesting a stronger constraint on the target outcome [83,202], which is expressed in terms of the necessity effect size (d) [83].³¹ Confirmation of a necessary condition requires at least a medium effect size ($d = > 0.10$) and a statistically significant permutation value ($p < 0.05$),³² whereas the absence of a ceiling zone and non-significance of NCA parameters (i.e. $d = < 0.10$ and $p > 0.05$) signify that a predictor is not a necessary condition [202].

NCA is supplemented by bottleneck tables [83], which provide a tabular representation of each ceiling line, wherein each row represents an outcome level and each column shows the minimum value of a given predictor that is required for securing the outcome level [205]. As a result, the bottleneck table provides information regarding the sequence in which predictors may become critical [201,205]. However, researchers should ensure that only constructs which qualify as necessary conditions are reported, whereas non-rejected conditions should be omitted from the bottleneck table [204] (see Section 6.6).

Following the introduction and application of NCA in 2016 [83,206,207], Dul and colleagues have defended the method [208,209], extended its usability [202],³³ and provided guidelines for good practice [204], while a range of research fields such as technology and innovation management [204] have adopted the technique [210]. For example, Jabeur [211] employed NCA to examine the relationship between renewable energy consumption and economic growth in France, while Rey-Martí [212] examined the factors needed to help compensate local communities for the negative environmental impacts of mining [212]. In a comprehensive study, Kazemzadeh et al. [213] employed NCA to examine the factors influencing carbon emission intensity in 94 countries, whereas Escadas and colleagues [203] examined whether emotions are essential for ethical awareness in consumer decision-making.

3.3.6. Combined use of PLS-SEM and NCA

Following the uptake of NCA, Richter and colleagues [84] established guidelines to encourage the combined use of PLS-SEM and NCA “as complementary views of causality and data analysis,” which can support theory development. Accordingly, the integration of NCA into

PLS-SEM can enable researchers “to identify the (‘must-have’) factors required for an outcome, that is necessity logic, as well as the (‘should-have’) factors that contribute to a high-level, namely additive sufficiency logic” [84].³⁴ Recommendations include using the rescaled values (0–100) of latent variable scores from IMPA when dealing with different scales (e.g. 5-point and 11-point scales) to support more robust comparison, as implemented in this study [84]. Drawing on the empirical scope of values via IMPA also supports a more conservative estimate of the effect size as compared to using the theoretical scope of 0–100 [87].

The efficacy of combining PLS-SEM and NCA has been demonstrated in diverse contexts such as carbon unlock for the transport sector [214], public transport use in European countries [215] and Nordic cities [216], adoption of electric motorcycles in Vietnam [217], institutional conditions for attracting foreign direct investment in Bulgaria [218], green competitive advantage in the organisational context [219], and consumer purchasing behaviour in Iran [220]. The practical implications of combining PLS and NCA are substantial in promoting more actionable insights for policy makers and stakeholders [84], which can be understood alongside results from IMPA [220] and more recently, cIMPA [87].

3.3.7. Combined importance-performance map analysis

Combined importance-performance map analysis (cIMPA) leverages data from PLS-SEM, IMPA, and NCA to support recommendations for strategic decision-making [87]. As with IMPA, importance is plotted on the x-axis to represent total effects in the PLS path model for corresponding predictors, while average performance is plotted on the y-axis according to the average rescaled latent variable scores. Additionally, the bottleneck percentage results from NCA are integrated into the output to enrich empirical insights [87].

The bottleneck percentages are visualised within the cIMPA by relative size of each predictor, as demonstrated by Hauff and colleagues [87] when operationalising an adapted version of the technology acceptance model (TAM) [221]. The model included emotional value, ease of use, usefulness, and compatibility as predictors of adoption intention and technology use [87]. For reaching a target of 85% technology use, emotional value proved a minor bottleneck (i.e. 6% of cases failed to achieve the required level), corresponding to a small circle in the cIMPA, whereas perceived usefulness represented the most significant bottle and largest circle (i.e. 47% of cases failed to reach the necessary minimum value) [87].

cIMPA assists in demarcating more clearly between multiple necessary conditions, which can be otherwise obscured when considering results from a traditional IMPA focused on additive sufficiency logic. Adhering to the guidelines established by Hauff et al. [87] vis-à-vis Dul and colleagues [202,204], researchers should ensure that a necessary condition has theoretical justification, in addition to an at least medium effect size that is statistically significant (i.e. $0.10 \leq d < 0.30$; $p < 0.05$). Furthermore, cIMPA should account for practical considerations within the case-context by focusing on a specific level of the target outcome and meaningful bottleneck dynamics [87].

3.3.8. Summary of methods

This study advances the use of combined mixed-methods data analysis by integrating PLS-SEM, NCA, and cIMPA, as illustrated in Fig. 4. Based on literature review, Section 4 lays the foundations for testing sufficiency- and necessity-grounded hypotheses in the context of

²⁸ The CR-FDH is less sensitive to outliers and measurement errors than the CE-FDH.

²⁹ In this case, comparatively more observations were above the ceiling zone, while negligible difference was reported between effect sizes for the CE-FDH and CR-FDH.

³⁰ X is on the horizontal axis increasing to the right; Y is on the vertical axis and increases upward [202].

³¹ i.e. the size of the empty space above the ceiling as a fraction of the total space where cases are observed (or could be observed given the minimum and maximum empirical or theoretical values of X and Y [83]).

³² The following guidelines are suggested in the literature: $0 < d < 0.1$ represents a small effect; $0.1 \leq d < 0.3$ indicates a medium effect, $0.3 \leq d < 0.5$ corresponds to a large effect, while $d \geq 0.5$ suggests a very large effect [202].

³³ Notably, Dul et al. [202] developed a statistical significance test for NCA to evaluate the null hypotheses of an observed effect being due to chance, which the authors described as an “approximate permutation test.”

³⁴ Four scenarios are possible: (1) the exogenous construct is a significant determinant and a necessary condition; (2) the exogenous construct is a significant determinant but not a necessary condition; (3), the exogenous construct is a non-significant determinant but not a necessary condition; and (4), the exogenous construct is a non-significant determinant and not a necessary condition.

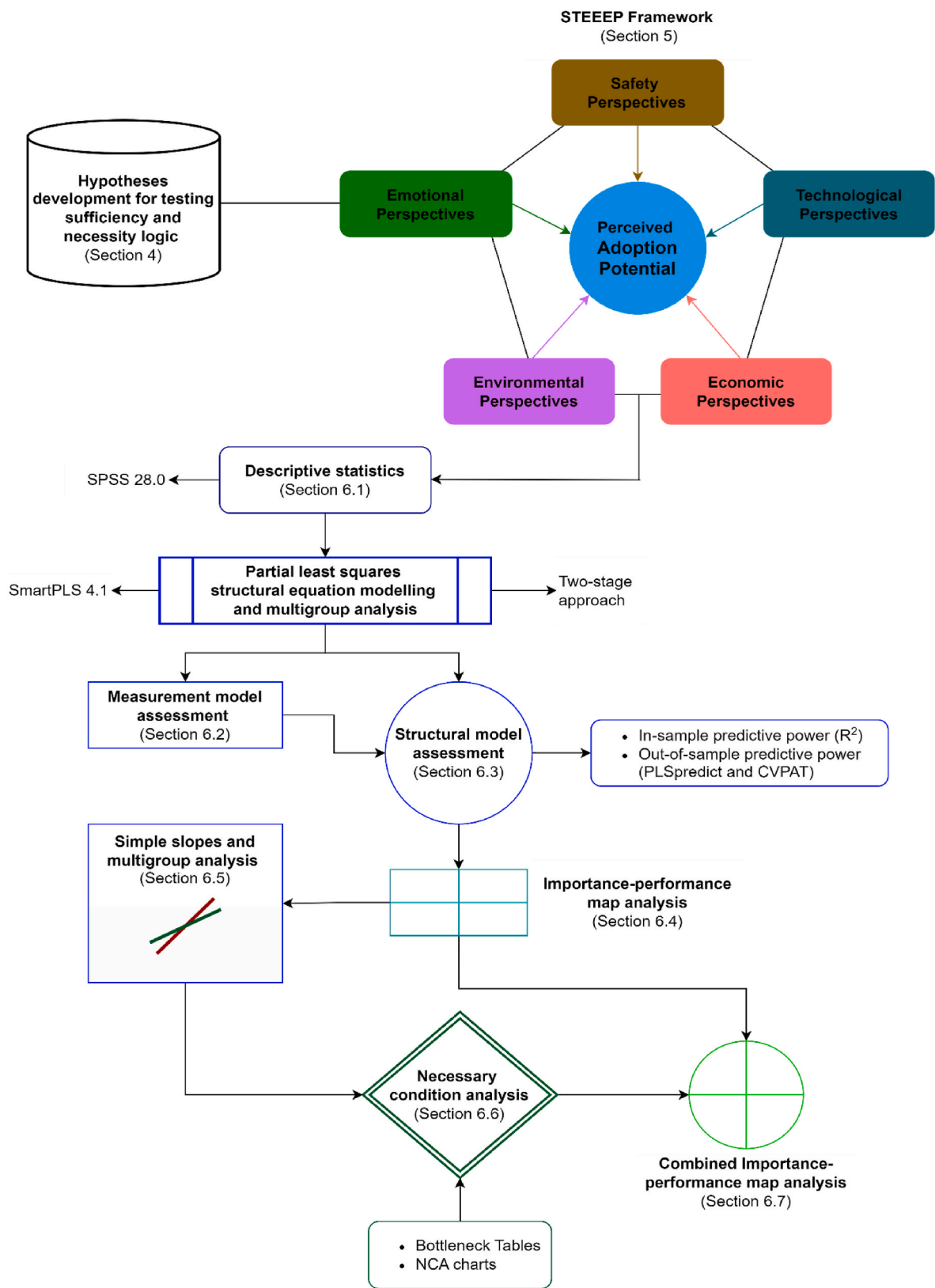


Fig. 4. Research steps and data analysis methods.

domestic hydrogen adoption potential, while Section 5 formalises the STEEEP Framework, which is adapted in Section 6.6.2 to deepen understanding of the technological dimension. Firstly, Section 6.1.2 reports descriptive results from the online survey, which includes a focus

on moderating variables. Next, PLS-SEM is carried out via the two-stage approach, following the measurement model assessment and structural model assessment in Section 6.2 and Section 6.3, respectively. Thereafter, the multi-stage empirical approach is supported by carrying out

IMPA in Section 6.4, simple slopes analysis and multigroup analysis in Section 6.5, NCA in Section 6.6, and finally, cIMPA in Section 6.7.

4. Hypotheses development for testing sufficiency and necessity logic

To formalise a conceptual framework for modelling perceived adoption potential for hydrogen homes, the following sub-sections review the supporting literature on HET acceptance and develop hypotheses for each construct.

4.1. Insights from the Domestic Hydrogen Acceptance Model

The first PLS-SEM-focused output from this dataset concentrated on the antecedents of domestic hydrogen acceptance, with an explicit focus on six dimensions: cognitive processes, social capital, environmental attitude, risk perceptions, cost-benefit appraisal, and affective response [76]. However, the proposed Domestic Hydrogen Acceptance Model (DHAM) was analysed solely from a sufficiency-based paradigm. As an entry point to integrating PLS-SEM and NCA to evaluate perceived adoption potential for hydrogen homes, it is instructive to firstly explore the necessary conditions for enabling social acceptance in line with Fig. 1. Leveraging insights from the DHAM provides a logical means to support necessary condition hypotheses in this emergent research context, as opposed to justifying observed relationships *ex post* [204].

Table 2 shows that only five constructs have an effect size, with two of the results (public trust and positive emotions) proving negligible. Production perceptions and perceived community benefits are the principal bottlenecks, which reflects the notion that coupling green hydrogen production to economic, social, and environmental benefits is a relevant parameter of domestic hydrogen acceptance [76], which has been further emphasised in the European context [12]. Additionally, but to a more marginal level, safety perceptions should reach a certain minimum threshold to enable domestic hydrogen acceptance, as reported in Table 3.

Although non-significant constructs can correspond to necessary conditions [216],³⁵ this relationship is not observed within the DHAM. It also noteworthy that significant negative predictors such as perceived socio-economic costs and disruptive impacts do not emerge as necessary conditions, since the presence of such constructs would counteract social

Table 2
Summary results of CR-FDH for the Domestic Hydrogen Acceptance Model.

Construct	Accuracy	Slope	Intercept	Effect size
Awareness	100	n/a	n/a	0.000
Knowledge	100	n/a	n/a	0.000
Public Trust	99.892	0.539	92.859	0.005 ^b
Production Perceptions	99.783	2.803	0.743	0.159 ^a
Safety Perceptions	99.729	4.166	16.399	0.085 ^b
Perceived Disruptive Impacts	100	n/a	n/a	0.000
Perceived Socio-economic Costs	100	n/a	n/a	0.000
Perceived Community Benefits	99.837	0.991	53.591	0.109 ^a
Positive Emotions	100	0.319	90.000	0.016 ^b
Negative Emotions	100	n/a	n/a	0.000

^a Moderate effect size.

^b Small effect size.

³⁵ For example, Sukhov et al. [216] found that security/safety had a non-significant effect on perceived accessibility of public transportation services for an ageing population ($\beta = -0.008$, $p = 0.888$) but was nevertheless a necessary condition for enabling the target outcome ($d = 0.097$, $p = 0.016$).

Table 3

Results for combined use of PLS-SEM and NCA for domestic hydrogen acceptance.

Construct	PLS-SEM results (path coefficient; <i>p</i> -value)	NCA results (<i>d</i> ; <i>p</i> -value)	Result
Awareness	−0.019; 0.217	0.000; <0.001	Non-significant determinant and not a necessary condition
Knowledge	−0.008; 0.608	0.000; <0.001	Non-significant determinant and not a necessary condition
Public Trust	0.198; <0.001	0.010; 0.110	Significant determinant but not a necessary condition
Production Perceptions	0.214; <0.001	0.159; <0.001	Significant determinant and a necessary condition
Safety Perceptions	0.058; 0.004	0.085 ^a ; <0.001	Significant determinant and a necessary condition
Perceived Disruptive Impacts	−0.092; <0.001	0.000; <0.001	Significant determinant but not a necessary condition
Perceived Socio-economic Costs	−0.058; 0.001	0.000; <0.001	Significant determinant but not a necessary condition
Perceived Community Benefits	0.276; <0.001	0.110; <0.001	Significant determinant and a necessary condition
Positive Emotions	0.217; <0.001	0.020; <0.001	Significant determinant but not a necessary condition
Negative Emotions	−0.138; <0.001	0.000; <0.001	Significant determinant but not a necessary condition

^a The result is marginally below the general guideline of $d > 0.1$ (CE-FDH: $d = 0.090$) but the construct qualifies as a relevant necessary condition in the context.

acceptance and be theoretically counterintuitive,³⁶ although such factors may potentially operate as restrictive necessary conditions [222].³⁷ Of the four possible scenarios presented in Fig. 5, only one necessary-condition combination is observed for three constructs, suggesting the dynamics of social acceptance could be relatively clear-cut.

By theorising a linkage between social acceptance and adoption intention (see Fig. 1), this study provides a first step in gauging the underlying complexity of potential bottleneck dynamics regarding perceived adoption potential for hydrogen homes. The approach departs from the DHAM, wherein perceived community benefits was operationalised as an antecedent of domestic hydrogen acceptance. Instead, the three measurement items of perceived community benefits (i.e. economic, social, and environmental benefits) are combined with three measures of willingness to adopt domestic hydrogen before 2030, resulting in a new hybrid construct: *perceived adoption potential*.

Developing new measurement items and constructs is a critical component of behavioural research, as reflected in the evolution of the TAM [221], UTAUT [187], and related derivatives [224,225]. For example, in the context of consumer satisfaction with modes of travel, Ettema et al. [226] developed a nine-item scale (i.e. Satisfaction with Travel Scale) to account for the cognitive and emotional antecedents. Subsequently, Friman et al. [227] observed that cognitive and affective dimensions are empirically distinct but also correlated in such a way to form a valid construct for measuring satisfaction with travel [215].

³⁶ In an exemplary study, Sukhov et al. [215] found that information had a (non-significant) negative effect on travel satisfaction ($\beta = -0.043$, $p = 0.399$) no necessity effect ($d = 0.000$, $p = 1.000$).

³⁷ i.e. the presence of a negative factors constrains the manifestation of the target outcome.

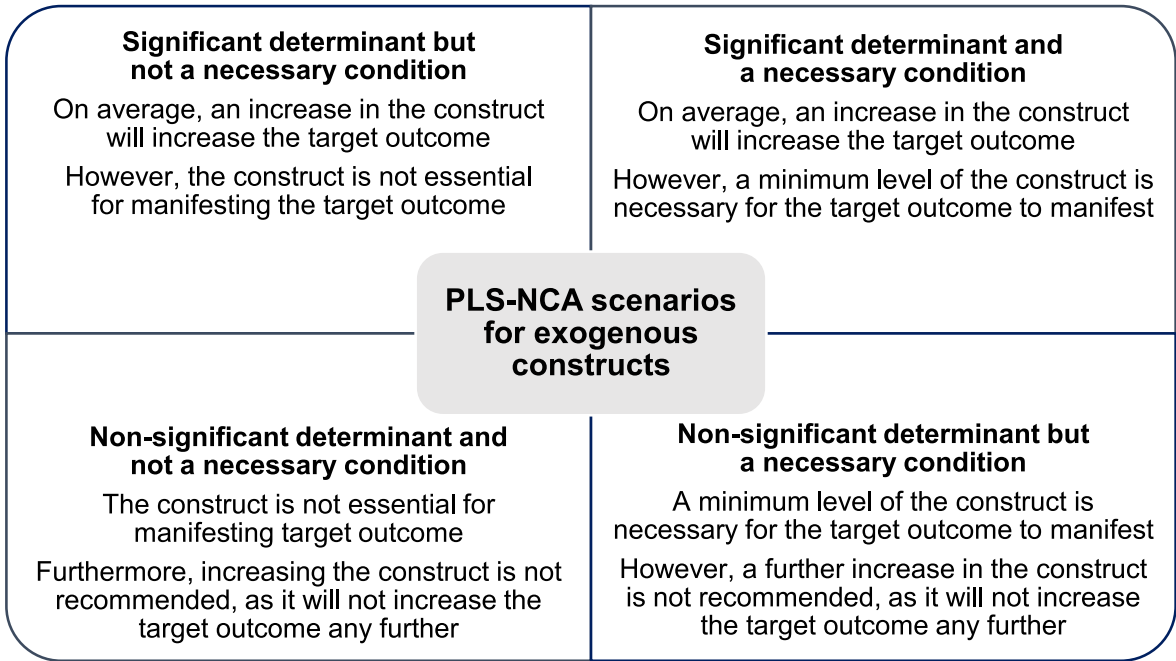


Fig. 5. Possible scenarios for results from combined use of PLS-SEM and NCA. Source: Authors’ design based on [84,223].

Accordingly, this study follows suit by leveraging the opportunity to develop and test a new endogenous construct for the first time.

Departing from the DHAM [76], the STEEP Framework operationalises two new constructs, namely, technology perceptions and financial perceptions, while retaining four constructs: safety perceptions, perceived socio-economic costs, production perceptions, and positive emotions. In view of this dichotomy, the literature review places primary focus on the newly introduced constructs (see Section 4.3 and Section 4.4), in addition to reviewing the emotional dimension from a necessity perspective in Section 4.7. Further contextual details and insights from the literature regarding safety perceptions, perceived socio-economic costs, and production perceptions are reported in Supplementary Note 12 and parallel analysis of this dataset [76,154]. Finally, this study introduces a new research angle compared to prior contributions from this research project [76,228,229] by focusing on the moderating effects of age, gender, and housing tenure status on perceived adoption potential, as outlined in Section 4.8.

4.2. Safety perceptions

Public perceptions of hydrogen safety are set to influence the feasibility of deploying hydrogen homes at scale [19]. Scientists broadly agree that hydrogen has a similar risk profile to other fuels such as natural gas and gasoline [230,231]. Furthermore, it is a precondition of deployment that hydrogen should be safe for transportation and storage, with pipelines and associated infrastructure being fit for purpose and non-hazardous [12]. To narrow the research gap and mitigate perception bias, this study operationalises a comparative assessment of safety perceptions by evaluating hydrogen fuel against natural gas across five metrics (see Section 6.1.2). Given that safety perceptions had a positive and significant effect on social acceptance when validating the DHAM [76] and a weak necessity effect (see Table 3), corresponding hypotheses are developed when testing the STEEP Framework:

- H1a.** Safety perceptions will have a significant positive influence on the perceived adoption potential of hydrogen homes.
- H1b.** A positive safety perception of domestic hydrogen relative to natural gas is a necessary condition for enabling the perceived adoption potential of hydrogen homes.

4.3. Technology perceptions

Establishing positive technology perceptions for low-carbon domestic energy technologies [232] underpins the premise of phasing out natural gas appliances to meet net-zero ambitions [233]. To date, low-carbon solutions such as heat pumps have failed to gain traction in the UK [234,235],³⁸ which provides a cautionary tale to diffusing other low-carbon heating technologies at scale, as intended by the UK government to reach net-zero by 2050 [40]. As communicated in the UK Hydrogen Strategy [43], it is imperative to generate comprehensive evidence regarding the consumer experience of using hydrogen boilers and hobs relative to other technologies before policy decisions can be taken. When consumer engagement is insufficient, public backlash may ensue and policy efforts may reach an impasse.

At present, perceptions related to the performance of hydrogen boilers and hobs remain highly underexplored by scholars [41], with a limited number of studies reporting basic insights [73].³⁹ To date, studies conducted in the UK observe an underlying preference to preserve the lived experience of gas heating and cooking [41,44], which would thereby minimise changes to current domestic energy practices [36]. Foremost, cooking technologies feature more prominently in daily routines and would therefore have greater scope to create a visible change to domestic life [32].

It follows that the socio-material nature of hobs and boilers may influence consumer perspectives [32]. Foreseeably, the main priority for consumers is that hydrogen boilers and hobs perform as well, if not better, than the incumbent technology [41]. To this point, a wide range of studies on low-carbon energy technologies [142,236,237] discuss the importance of ‘relative advantage’⁴⁰ [125] in the context of consumer

³⁸ Heat pumps are installed in ~1% of UK homes [235].
³⁹ Conversely, the potential for hydrogen heating technologies [34,382] has been recognised in countries such as Japan, USA, Germany, and the UK since the early 2000s [383]. Nevertheless, progress in RD&D has been relatively laggard [384,385] due to a range of techno-economic, technical, policy and market barriers [19].
⁴⁰ Relative advantage can be defined as “how consumers perceive the potential benefits of domestic hydrogen over the incumbent technology (i.e. natural gas appliances)” when considering technology attributes [77].

decision-making.

Qualitative findings from online focus groups conducted in the UK suggest a mixed picture, with positive expectations as well as concerns regarding the user benefits of hydrogen boilers and hobs [41]. Nevertheless, most participants believed hydrogen-fuelled technologies would provide a smarter and more efficient service compared to gas boilers and hobs [41]. To address the current knowledge gap in respect to performance expectancy and underlying technology perceptions of hydrogen heating and cooking, the following set of hypotheses are formulated:

H2a. The perceived performance of hydrogen boilers will have a positive influence on technology perceptions for domestic hydrogen.

H2b. A positive perception of hydrogen boiler performance relative to natural gas boilers is a necessary condition for enabling a perceived technology advantage.

H2c. The perceived performance of hydrogen boilers will have a positive influence on the perceived adoption potential of hydrogen homes (*Adapted STEEP Framework*).

H2d. A positive perception of hydrogen boiler performance relative to natural gas boilers is a necessary condition for enabling the perceived adoption potential of hydrogen homes (*Adapted STEEP Framework*).

H3a. The perceived performance of hydrogen hobs will have a positive influence on technology perceptions for domestic hydrogen.

H3b. A positive perception of hydrogen hob performance relative to natural gas hobs is a necessary condition for enabling a perceived technology advantage.

H3c. The perceived performance of hydrogen hobs will have a positive influence on the perceived adoption potential of hydrogen homes (*Adapted STEEP Framework*).

H3d. A positive perception of hydrogen boiler performance relative to natural gas boilers is a necessary condition for enabling the perceived adoption potential of hydrogen homes (*Adapted STEEP Framework*).

H4a. Technology perceptions associated with hydrogen boilers and hobs will have a positive influence on the perceived adoption potential of hydrogen homes.

H4b. A positive technology perception of hydrogen boilers and hobs relative to natural gas appliances is a necessary condition for enabling the perceived adoption potential of hydrogen homes.

4.4. Financial perceptions

Financial factors are typically among the foremost considerations when consumers decide to purchase new technologies [238] or otherwise evaluate hypothetical scenarios such as choosing between hydrogen boilers and heat pumps [137]. Currently, investment costs present a major barrier to diffusing domestic micro-generation technologies [71,239], which may aggravate energy vulnerabilities [240,241]. Notably, results from recent large sample UK studies⁴¹ showed that 45% of respondents were concerned about the potential installation cost of a low-carbon heating system, whereas 25% were concerned about potential running costs [144].

Although the evidence base remains nascent, researchers have highlighted the importance of cost factors in shaping prospects for domestic hydrogen adoption [75,242,243]. Financial perceptions may prove particularly decisive to consumers grappling with fuel poverty or high levels of fuel stress [115,244], which is reflected in the emerging literature on domestic hydrogen acceptance [73,117]. Specifically,

Sandri et al. [115] examined household energy vulnerability in the context of Australia's prospective transition to hydrogen homes, following previous national studies highlighting the relevance of micro-economic factors such as willingness-to-pay [245,246].

Engaging with households facing socio-economic hardship in the North of England, Scott and Powells [242] found that 77% of survey respondents (N = 742) were unable or unwilling to pay for higher energy bills. Similarly, a follow-up study (N = 700) cited affordability as the most significant barrier to supporting hydrogen homes [73]. In parallel, Fylan et al. [138] highlighted that purchasing costs could present the most significant short-term barrier to domestic hydrogen adoption in the UK. In the Welsh context, Thomas et al. [148] caution that social resistance is near inevitable should residential decarbonisation contribute towards an increase in UK energy bills. As a result, the UK public appear adamant that the personal costs of the domestic hydrogen transition should be compensated within an adequate time-frame [243], which reflects underlying expectations for sizeable subsidy schemes [117,130].

Calvillo et al. [247] stress the need for cost equivalence between domestic hydrogen and natural gas to promote consumer acceptance and prospective adoption. This requirement is reflected by a recent 'price promise' towards delivering affordable low-carbon boilers, as presented by the 'big four' boiler manufacturers in 2021 [248].⁴² Mirroring this trajectory, UK focus group respondents (N = 58) believed hydrogen boilers and hobs should achieve cost parity with natural gas appliances, provided appropriate subsidies and incentives are in place [130]. It follows that the cost-competitiveness of hydrogen homes will influence the scope for large-scale adoption. In conjunction with results reported in (see Table 3), the following hypotheses account for market acceptance by evaluating financial perceptions in a holistic way [44]:

H5a. Financial perceptions regarding the purchasing and running costs of hydrogen boilers and hobs will have a negative influence on the perceived adoption potential of hydrogen homes.

H5b. As a negative predictor, the absence of financial perceptions will not constrain the perceived adoption potential of hydrogen homes.

4.5. Perceived socio-economic costs

Typically, hydrogen acceptance studies place a stronger focus on perceived safety risks [165,249] and a greater emphasis on perceived benefits [250,251] as opposed to socio-economic costs [94]. To date, the perceived socio-economic costs of the hydrogen transition are yet to be explored in depth by the research community [19], despite mounting societal concerns over fuel stress and energy security (see SN12), which are pronounced in the UK context [252].

At present, communities in the UK appear sceptical about local economic benefits and more concerned about potential risks, as suggested by the collapse of the Whitby village trial [62,64]; reflected by the significant negative influence of perceived socio-economic costs on domestic hydrogen acceptance [76]. In response, this study concentrates on the macro-economic risks of transitioning to hydrogen homes, which will have a bearing on socio-political and market acceptance [77,253].

The developed construct is composed of two closely related areas, namely, the perceived impacts of the domestic hydrogen transition on energy (in-)security and fuel poverty, as reported in SN1. Notably, these two areas remain highly interrelated and may impede ambitions to diffuse hydrogen homes at scale [76]. The following hypotheses are developed to address the knowledge gap on perceived socio-economic costs in hydrogen studies [94,254], which also remains an overlooked construct in the broader literature on technology acceptance [255]:

H6a. The perceived socio-economic costs of transitioning to hydrogen

⁴¹ Specifically, the Department for Business, Energy & Industrial Strategy (BEIS) Public Attitudes Tracker (PAT) carried out in during the Winter of 2021 (N = 1551) and 2022 (N = 1621).

⁴² Worcester Bosch, Baxi, Vaillant, and Ideal.

homes will have a negative influence on the perceived adoption potential of hydrogen homes.

H6b. As a negative predictor, the absence of perceived socio-economic costs will not constrain the perceived adoption potential of hydrogen homes.

4.6. Production perceptions

The UK Hydrogen Strategy [33] proposes a ‘twin-track’ production approach, which involves steam methane reformation (SMR) and carbon capture and storage (CCS), otherwise referred to as ‘blue’ hydrogen, alongside renewable-based (i.e. ‘green’) hydrogen (see SN12). To date, a single small-sample study has examined public perceptions of the twin-track approach, reporting 39% of respondents to be very supportive and 46% to be somewhat supportive [131]. Although the underlying strategy was broadly supported, focus group participants conveyed a lack of clarity about the merits of the twin-track approach, following misconceptions about its underlying premise and the role of blue hydrogen [77]. Furthermore, environmentally engaged citizens were more inclined to critique the blue component of the twin-track approach, resulting in pockets of resistance and scepticism [131].

Accounting for these dynamics and findings from international studies [75,105,256–258] (see SN12), this study evaluates support levels for the twin-track policy, thereby subsuming both technology pathways into one construct, which may reflect environmental perceptions and awareness of net-zero. Given that production perceptions functions as a critical driver of domestic hydrogen acceptance, the following hypotheses are tested in this study:

H7a. Production perceptions will have a significant positive influence on the perceived adoption potential of hydrogen homes.

H7b. Support for green and blue hydrogen production pathways is a necessary condition for enabling the perceived adoption potential of hydrogen homes.

4.7. Positive emotions

The emotion-based mechanisms underlying consumer attitudes towards energy technologies has attracted increased attention from scholars in recent years [259–261]. In a relatively early contribution to the literature based on a small sample of participants recruited from Vanderbilt’s eLab consumer panel ($N = 94$), Truelove [262] demonstrated the efficacy of an affective-based model for predicting natural gas reliance and facility siting in the United States.⁴³

Subsequently, Visschers and Siegrist [263] measured positive emotions (i.e. pride, satisfaction, and enthusiasm) and negative emotions (i.e. fear, anger, nervousness, and threat) when modelling consumer attitudes towards solar, nuclear, hydropower, gas-fired power, and wind power in the German-speaking region of Switzerland ($N = 863$). Notably, positive emotions towards natural gas were higher among male respondents ($M = 2.05$, $SD = 0.05$) than female respondents ($M = 1.92$, $SD = 0.07$), with results for negative emotions mirroring this divergence (Male: $M = 3.00$, $SD = 0.08$; Female: $M = 3.42$, $SD = 0.11$), as evaluated via a 7-point Likert scale [263].

With growing scholarly focus on the emotional aspects of the sustainable energy transition [264–266] and climate-related emotions [267], hydrogen researchers have responded by evaluating the affective

dimension of social acceptance using SEM [76,268] and other regression-based techniques [269,270]. As depicted in Fig. 1 and posited within the unified theory of domestic hydrogen acceptance [77], the prospective transition to hydrogen homes will be shaped by the interplay between cognitive and emotional antecedents, alongside other factors.

Qualitative insights from this dataset signalled a degree of positivity towards domestic hydrogen, with 23% and 14% of respondents expressing optimism or hope ($N = 1213$) [229]. In parallel, positive emotions proved a more significant predictor of social acceptance than negative emotions, as reported in (see Table 3). However, emotional antecedents are yet to be explored through a necessity-based paradigm.

Support for this research trajectory is evident in the contribution of Escadas et al. [203], which investigated whether emotions are necessary conditions for consumer ethical decision-making in the Portuguese context ($N = 415$). The study found that ethical behaviour is contingent on certain levels of positive emotions (i.e. happiness, gladness, and satisfaction), whereas negative emotions proved non-essential for the target outcome. Furthermore, in pioneering the combined use of PLS-SEM and NCA, Richter et al. [84] found that positive emotional value (i.e. enjoyment, pleasure, and relaxation) is the most significant necessary condition for intended adoption of e-books ($d = 0.214$, $p < 0.001$), while also having a strong effect on adoption intention within the path model ($\beta = 0.515$, $p < 0.001$).

Against this background, the STEEP Framework focuses exclusively on the role of positive emotions in shaping adoption prospects for hydrogen homes, thereby testing whether the construct operates distinctly at different stages of the innovation-decision process:

H8a. Positive emotions will have a significant influence on the perceived adoption potential of hydrogen homes.

H8b. Positive emotions is a necessary condition for enabling the perceived adoption potential of hydrogen homes.

4.8. Moderating effects of socio-demographic variables

Prior studies demonstrate the relevance of a range of socio-demographic variables as potential predictors of hydrogen acceptance [271], which is reflected in studies on the residential context [44]. Among key findings reported by Gordon et al. [44], males generally express more support for hydrogen than females [75,116,245,272], while higher income and education levels also exert a positively influence on hydrogen acceptance [140,245]. In the Australian context, 65% of male respondents proved *very supportive* or *supportive* of domestic hydrogen compared to 40% for female respondents [245], while Norwegian males scored 0.66 points higher on a seven-point hydrogen acceptance scale than females [105].

Hydrogen acceptance has also proved context-dependent in Australia, with socio-economic characteristics and geographic location having a significant influence [141]. Moreover, a recent study examining local acceptance of a hydrogen fuelling station (HFS) in South Korea reported the following results: a significant positive effect for higher income and education; a significant influence for location (metropolitan or non-metropolitan); and a significance negative effect for number of occupants per property [273]. Given that hydrogen home appliances would involve a more direct and frequent consumer experience compared to community level infrastructure such as HFSs, socio-structural characteristics are likely to influence consumer attitudes.

While prior research on low-carbon residential heating systems has examined housing-related variables [142,236], these aspects remain largely underexamined in the context of adoption potential for hydrogen homes. By contrast, an extensive longitudinal evidence base indicates that males hold more favourable attitudes towards computer technology use than females, however, the disparity is characterised by relatively small effect sizes [274,275]. Nevertheless, results from meta-analysis

⁴³ Feelings towards natural gas proved inherently neutral ($M = 3.06$, $SD = 0.66$), whereas wind power was viewed more positively ($M = 3.46$, $SD = 0.56$), with coal and nuclear perceived somewhat negatively ($M = 2.56$, $SD = 0.90$; $M = 2.45$, $SD = 0.93$), as measured on a 5-point Likert scale. The study also incorporated affective-based, cognitive-based, and combined models showing different levels of explanatory power across technologies.

suggest males have stronger belief in the societal usefulness of technology [275]. To an extent, research findings broadly echo the notion that gender may influence consumer perceptions towards emerging energy technologies in the residential context, suggesting males are more likely to be early adopters [276–279]. However, regarding solar PV adoption, Ruokamo et al. [280] caution that statistical results may fail to elucidate whether responses reflect decisions made at the individual or household level.

In view of the inherent complexities involved in rigorously examining the effect of socio-demographic and socio-structural variables, this study adopts a two-fold approach by firstly measuring the moderating effects of gender, age, and housing tenure on specific attributes of perceived adoption potential across the full sample. For example, it can be hypothesised that mortgage owners could feel less insulated from potential macro-economic risks compared to property owners, while younger demographics may be less sensitive to economic concerns at the household level (i.e. since financial involvement is positively correlated with age). At the same time, males may be less concerned about potential socio-economic costs due to higher levels of annual income (see Figs. 2b and 3a), in addition to being more pro-hydrogen technology in general.

Following simple slopes analysis, a multigroup analysis approach is applied by systematically comparing a sub-sample of male and female respondents to extend the evidence base. Accordingly, two additional hypotheses are tested to support the empirical analysis:

H9a. Gender, age, and housing tenure will have a moderating effect on the influence of specific predictors of perceived adoption potential for hydrogen homes.

H9b. The antecedents and levels of perceived adoption potential for hydrogen homes will differ significantly between male property owners aged 55+ and female mortgage owners 18–34 years old.

5. Conceptual framework

An overview of the hydrogen acceptance literature illustrates ways in which the field has evolved over time, as well as areas where research has seemingly stagnated or plateaued [94,120]. One of the earliest (qualitative) models conceptualised hydrogen (fuel) acceptance to be composed of a combination of values, perceptions and wants, which are influenced by social background and personal experience [93]. Although the model in question accounted for socio-psychological dynamics, the specific dimensions of acceptance were limited mostly to risk perceptions and customer satisfaction [93], thereby presenting a somewhat narrow lens.

Gordon et al. [44] reviewed the available literature on domestic hydrogen acceptance in 2022 ($N = 17$),⁴⁴ wherein Scott and Powells [42,73]⁴⁵ applied social practice theory [281] to explore social acceptance in the North of England ($N = 700$). Respondents had positive expectations for environmental benefits (69.9%) while economic benefits were less anticipated (23.4%), whereas safety perceptions proved mostly neutral (68.9%) [73]. Accounting for the emerging evidence base on hydrogen homes, the proposed framework expands on prior studies by focusing on the safety, technological, economic, environmental, and emotional perspectives shaping perceived adoption potential (see Fig. 6).

To create a valid and comprehensive construct for evaluating perceived adoption potential, six indicators are included as outlined in Section 4.1: three measuring willingness to adopt (boiler, hob, and both

technologies), and three measuring perceived community benefits (economic, social, and environmental). Crucially, perceptions related to community benefits will shape local and broader socio-political acceptance [253], in addition to influencing the potential for domestic hydrogen adoption [73,130]. The selected dimensions are of critical importance to the energy transition, as specified within the UK Hydrogen Strategy [33]. Alignment between techno-economic, technical, market, political and social dimensions [19] is required to develop national hydrogen economies in support of green growth and cross-sectoral decarbonisation [33].

6. Results

6.1. Descriptive statistics

6.1.1. Consumer knowledge about hydrogen

Survey respondents were asked ten questions to assess their objective knowledge of hydrogen. Each question consisted of a statement about hydrogen that was either true or false, and respondents were instructed *Please do not guess*. The assessment included five general knowledge questions, followed by five questions with a more scientific or technical focus (see Table 4).

Across the sample, respondents typically answered three to four questions correctly ($M = 3.38$, $SD = 2.16$), as illustrated in Table 4. Interestingly, general knowledge ($M = 31.40\%$, $SD = 19.58$) and technical knowledge of hydrogen ($M = 36.54\%$, $SD = 15.01$) proved comparable. The finding implies that consumers have similar levels of knowledge about the hydrogen industry or hydrogen economy compared to scientific understanding (see SN13). Critically, the findings highlight that factual understanding of hydrogen is extremely low in the UK, which has proved largely the case in other national contexts [75, 108,116,282].

Media representations are often the primary source of knowledge for most consumers [44], which may present a significant barrier towards developing ‘informed beliefs about hydrogen technologies’, as highlighted by Scovell and Walton [283] in the Australian context. This tendency motivates the need for information provision materials when conducting consumer research on emerging energy technologies [284, 285] such as hydrogen [139,141,258].

6.1.2. Consumer perspectives of domestic hydrogen adoption

Ahead of undertaking PLS-SEM, descriptive results for each construct indicator composing the STEEP Framework (see Fig. 6) display several important patterns, as reported in Table 5. Firstly, consumers perceive the safety credentials of different parts of the hydrogen ecosystem to be somewhat homogenous (see Fig. 7a). Additionally, consumer confidence in the efficiency and smart performance of hydrogen boilers and hobs is higher compared to perceived ease-of-use and effort expectancy. Notably, consumers anticipate a potential price hike in purchasing hydrogen technologies, whereas running costs are anticipated to be somewhat more comparable to natural gas (see Fig. 7b).

Critically, the online survey coincided with an unprecedented increase to the energy price cap⁴⁶ during the final quarter of 2022 [130], peaking at an annual high of £3,549, compared to £1277 in October 2021 [286]. Consequently, in October 2022, the government introduced an energy price guarantee (EPG)⁴⁷ of £2500 to help alleviate economic pressures [287]. These developments transmit the importance of contextual factors when evaluating the micro- and macro-economic dimensions of technology adoption, as reflected by concerns over energy

⁴⁴ Seven studies focused exclusively on domestic hydrogen, while 10 studies had a selective focus. Nine studies were conducted in the UK.

⁴⁵ One study combined a nationally representative survey ($N = 700$) with paper-based surveys ($N = 102$) [73], while the other integrated paper-based surveys ($N = 100$) with follow-up interviews [32].

⁴⁶ Set twice a year and regulated by the Office for Gas and Electricity Markets (Ofgem) to a limit the unit rate and standing charge that energy suppliers can charge for standard variable tariffs.

⁴⁷ A government subsidy introduced to limit the charges per unit of gas or electricity.



Fig. 6. Safety-Technological-Economic-Environmental-Emotional-Perspectives (STEEEP) Framework for measuring the perceived adoption potential of hydrogen homes.

Table 4
Survey responses to factual questions on hydrogen fuel.

Factual statement on hydrogen	Correct answer	Correct response (%)
General knowledge statements (OK 1–5)		
Hydrogen can be used to power road vehicles such as buses and cars	True	56.80
Hydrogen is traded around the world like other energy commodities	False	13.49
Currently, hydrogen production relies mainly on biomass/bioenergy	False	11.49
Hydrogen is mainly used in the refining and chemical sectors	True	30.79
Hydrogen has been used as rocket fuel for space exploration	True	44.44
Technical knowledge statements (OK 6–10)		
Hydrogen is heavier than air	False	30.73
Hydrogen is an odourless gas	True	60.49
Hydrogen emits carbon dioxide when burned	False	34.25
Hydrogen burns with an invisible flame	True	37.94
Hydrogen cannot be used to store energy produced from other sources	False	19.30

insecurity and fuel poverty.

It is apparent that the ‘colour labels’ [288,289] of hydrogen production methods [290] transmit important environmental cues to the public [105,256], which influence their support for associated technologies. However, the observed trends contradict the premise of the twin-track approach, whereby blue hydrogen is envisioned to enable a long-term trajectory towards a green hydrogen economy [33]. Conversely, respondents expressed comparatively more support for green hydrogen in the short-term and blue hydrogen in the long-term when considering each pathway in isolation. Overall, the results reflect the need to secure the low-carbon credentials of hydrogen-fuelled heating and cooking in the residential context. Nevertheless, Fig. 7a

raises significant questions over the extent to which the public may understand the tenets of the twin-track production strategy (Section see 4.6).

Finally, at the level of perceived adoption potential, there is minimal discrepancy between preferences for hydrogen boilers or hobs, while the combined prospect of a hydrogen home fails to increase willingness levels. It may be inferred that a hydrogen home may not necessarily prove more desirable than either technology in isolation, which contradicts previous findings from online focus groups conducted in the UK [41].

6.2. Measurement model assessment

The STEEP Framework examines the direct effects of five exogenous constructs (safety perceptions, financial perceptions, perceived socio-economic costs, production perceptions, and positive emotions), and one higher-order construct (technology perceptions) which is composed of two sub-constructs (perceived boiler performance and perceived hob performance).

Each exogenous construct is measured reflectively since the indicator items are closely correlated and interchangeable [291] and therefore influenced by an underlying latent construct [292,293]. However, the higher-order construct is measured as reflective-formative, with the arrows from perceived boiler performance and hob performance pointing towards technology perceptions [294]. When measuring reflective constructs, four criteria should be fulfilled, namely, item reliability, internal consistency reliability, convergent validity, and discriminant validity [293].

To support item reliability, indicator loadings should ideally exceed the more stringent Cronbach Alpha (CA) value of 0.708 [82,295].⁴⁸ In

⁴⁸ When this condition is met, it implies that the construct explains more than 50% of the variance in an associated indicator [82].

Table 5

Summary of descriptive findings for exogenous and endogenous constructs in the STEEEP framework.

Construct	Summary of descriptive results at the indicator level
Safety Perceptions (SP)	<ul style="list-style-type: none"> The combined measure of safety perceptions (SP5: $M = 5.96$) proved marginally higher than individual perceptions Negligible difference between hydrogen boiler (SP1: $M = 5.93$) and hydrogen hob (SP2: $M = 5.92$), followed by transport (SP3: $M = 5.80$) and lastly, storage (SP4: $M = 5.68$), as measured via an 11-point scale
Perceived Boiler Performance (BLR)	<ul style="list-style-type: none"> Respondents expect hydrogen boilers to be more energy efficient (BLR2: $M = 7.83$) than their natural gas counterparts, in addition to anticipating a comparatively smarter heating system (BLR4: $M = 7.33$) Hydrogen boilers are expected to provide a higher level of thermal comfort (BLR1: $M = 6.69$) compared to natural gas boilers, whereas expectancy levels for improved ease-of-use (BLR3: $M = 6.33$) proved least pronounced, as measured via an 11-point scale
Perceived Hob Performance (HOB)	<ul style="list-style-type: none"> Respondents also expressed a greater expectation for higher efficiency for hydrogen hobs (HOB1: $M = 6.75$), followed by smart performance (HOB4: $M = 6.32$) There was lower expectancy that hydrogen hobs would be easier to maintain and clean (HOB3: $M = 5.91$) or provide better cooking control compared to natural gas hobs (HOB2: $M = 5.85$), as measured via an 11-point scale
Financial Perceptions (FP)	<ul style="list-style-type: none"> Consumers anticipate that hydrogen boilers would be significantly more expensive to purchase than gas boilers (FP1: $M = 4.036$), while financial perceptions of gas hobs proved comparable (FP2: $M = 3.99$) Negative perceptions are less pronounced when considering energy bills for hydrogen compared to natural gas (FP3: $M = 3.14$), as measured via a 5-point Likert scale
Perceived Socio-economic Costs (PSC)	<ul style="list-style-type: none"> Concerns regarding fuel poverty impacts (PSC2: $M = 2.98$) exceeded worries over energy security ($M = 2.78$) in the context of switching from natural gas to hydrogen, as measured via a 5-point Likert scale
Production Perceptions (PP)	<ul style="list-style-type: none"> Greater support for green hydrogen production in the short-term (PP3: $M = 7.28$, $SD = 2.06$), followed by blue hydrogen production in the long-term (PP2: $M = 6.78$, $SD = 2.04$), green hydrogen production in the long-term (PP4: $M = 6.44$, $SD = 1.74$), and blue hydrogen production in the short-term (PP1: $M = 5.57$, $SD = 2.00$) Overall perceptions of the twin-track approach (PP5: $M = 5.68$, $SD = 1.82$) proved more conservative compared to blue hydrogen production after 2030, and green hydrogen production across both timeframes Green hydrogen production ($M = 6.86$) is favoured over blue hydrogen ($M = 6.17$) when accounting for both time horizons, as measured via an 11-point scale
Positive emotions (PE)	<ul style="list-style-type: none"> Optimism proved the strongest positive emotion ($M = 3.15$, $SD = 1.00$), followed by satisfaction ($M = 3.05$, $SD = 0.99$), calm ($M = 3.01$, $SD = 0.98$), and confidence ($M = 3.007$, $SD = 0.98$) regarding the prospect of using a hydrogen boiler and hydrogen hob, as measured via a 5-point Likert scale
Perceived Adoption Potential (PAP)	<ul style="list-style-type: none"> Consumer perceptions proved marginally more positive for hydrogen boilers (PAP1: $M = 2.94$, $SD = 1.00$), followed by hydrogen hobs (PAP2: $M = 2.98$, $SD = 1.01$), and lastly, hydrogen homes (PAP3: $M = 2.87$, $SD = 1.04$), as measured via a 5-point Likert scale Regarding perceptions of community benefits, respondents attributed most importance to environmental benefits (PAP6: $M = 7.02$), while economic (PAP4: $M = 6.28$) and social benefits (PAP5: $M = 6.23$) were comparable, as measured via an 11-point scale

this study, all indicators met this requirement with two exceptions: BLR3 = 0.668 and PP1 = 0.550. However, it was justified to retain both indicators to uphold content validity since CA is at least 0.50 [296], while other reliability and validity requirements were met.

Composite Reliability (CR) provides a measure of homogeneity or internal consistency between a set of indicators, which is supported when values exceed 0.70 [291]. As reported in Table 6, ρ_A fell between the recommended values of 0.70 and 0.90 for all constructs, except for safety perceptions which measured 0.92. Nevertheless, this construct fell below the less stringent upper threshold of 0.95, which established content validity and suggested indicator redundancy was not an issue [82].

Convergent validity assesses whether each construct converges to explain the variance of its indicators [82], which was verified since the average variance extracted (AVE) exceeded 0.50 for all constructs [291, 297], as reported in Table 6. Finally, discriminant validity refers to whether a construct can be considered empirically distinct within the model [82]. Following the heterotrait-monotrait (HTMT) ratio of correlations [298] and Fornell Larcker criterion [299], required thresholds were met to establish discriminant validity (see Table 7 and Table 8). Finally, variance inflation factor (VIF) scores were below the more stringent threshold of 3.0 in all cases, suggesting no instances of multicollinearity [295].

6.3. Structural model assessment

The bootstrapping procedure (10000 sub-samples) was applied in SmartPLS 4.1 [300] to test the proposed hypotheses. As reported in Table 9, all results proved statistically significant at the less than 0.1% level, thereby supporting the robustness of the conceptual framework. Following the STEEEP Framework, respondents do not view hydrogen to be less safe than natural gas when considering hydrogen boilers and hobs, as well as pipeline transport and underground storage (see Figs. 7a and 8). Accordingly, safety perceptions has a significant positive influence ($\beta = 0.193$, $t = 9.679$) on perceived adoption potential for hydrogen homes.

Results for the higher-order construct, technology perceptions ($\beta = 0.179$, $t = 8.674$) confirm the importance of consumer expectations for boiler performance ($\beta = 0.474$, $t = 62.875$) and hob performance ($\beta = 0.630$, $t = 70.332$) in shaping underlying attitudes towards hydrogen homes (see Fig. 8 and SN15). The indirect positive effect of perceived boiler performance (BLR: $\beta = 0.085$, $t = 8.509$, $\rho < 0.001$) and perceived hob performance (HOB: $\beta = 0.113$, $t = 8.780$, $\rho < 0.001$) on perceived adoption potential proved near equivalent when modelled as a higher-order construct, but deviate more significantly when modelled independently as discussed in Section 6.6.2.

In respect to potential micro- and macro-economic impacts, respondents appear somewhat more concerned about broader socio-economic costs ($\beta = -0.126$, $t = 8.409$) than personal financial costs ($\beta = -0.082$, $t = 5.311$). Production perceptions related to the twin-track approach are positively associated with perceived adoption potential ($\beta = 0.241$, $t = 13.441$). Furthermore, positive emotions support adoption prospects for hydrogen homes above other factors ($\beta = 0.376$, $t = 19.909$).

Consequently, positive emotions is the most influential construct within the model ($f^2 = 0.284$). Although positive emotions has a moderate effect size (i.e. ≥ 0.15), all other constructs have a small effect (i.e. $\geq 0.02 < 0.15$), with production perceptions ranking highest ($f^2 = 0.116$), followed by safety perceptions ($f^2 = 0.068$), technology perceptions ($f^2 = 0.063$), and perceived socio-economic costs ($f^2 = 0.036$). Lastly, financial perceptions ranks as the least influential predictor of perceived adoption potential, corresponding to an insignificant effect size ($f^2 = 0.016$).

6.3.1. In-sample predictive power

As a measure of in-sample explanatory power, the coefficient of

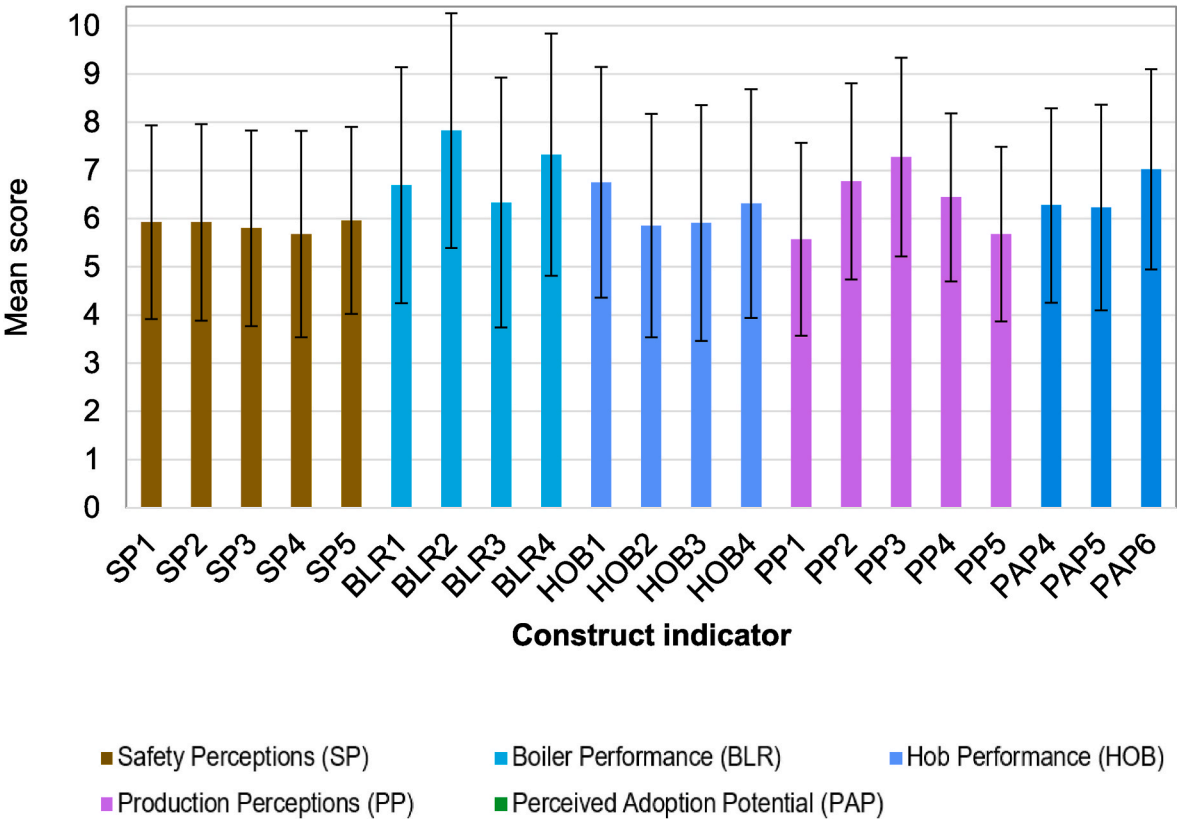


Fig. 7a. Constructs measured on eleven-point Likert scale.

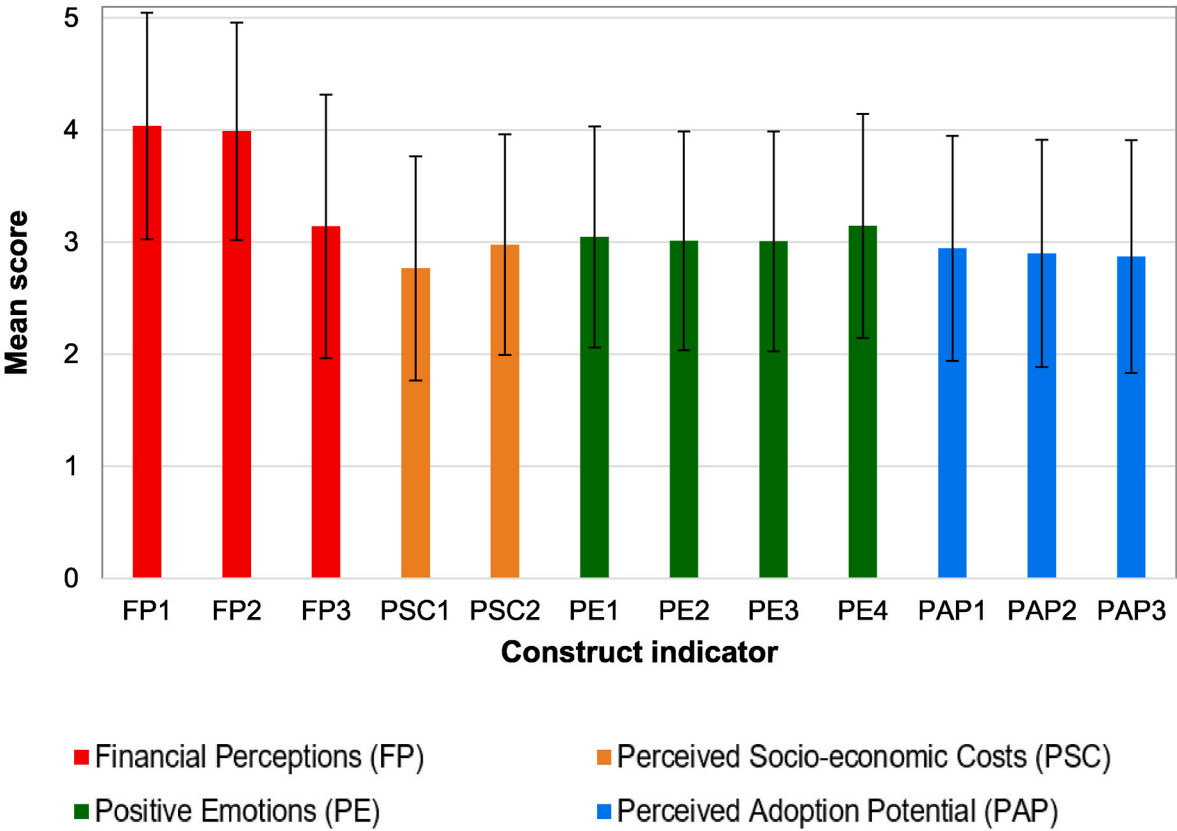


Fig. 7b. Constructs measured on a five-point Likert scale.

Table 6
Assessment of reliability, convergent validity, and multicollinearity.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety Perceptions	0.918	0.920	0.939	0.754	1.411
Boiler Performance ^a	0.723	0.729	0.828	0.548	1.662
Hob Performance ^a	0.852	0.853	0.900	0.693	1.662
Technology Perceptions ^b	0.774	0.774	0.898	0.816 ^c	1.302
Financial Perceptions	0.732	0.827	0.827	0.615	1.067
Perceived Socio-economic Costs	0.730	0.733	0.881	0.787 ^d	1.127
Production Perceptions	0.816	0.845	0.870	0.578	1.291
Positive Emotions	0.881	0.885	0.918	0.737	1.284
Perceived Adoption Potential	0.855	0.854	0.892	0.581	n/a

^a Higher-order construct.
^b Lower order constructs.
^c Results for validating the higher order construct (TP) are reported in SN14.
^d Since PSC has two indicators, the AVE is by default larger than 0.50.

Table 7
Heterotrait-monotrait results for assessment of discriminant validity.

	PAP	BLR	FP	HOB	PSC	PE	PP	SP
PAP								
BLR	0.537							
FP	0.273	0.199						
HOB	0.492	0.803	0.104					
PSC	0.423	0.210	0.224	0.183				
PE	0.721	0.333	0.211	0.315	0.249			
PP	0.616	0.298	0.104	0.310	0.329	0.404		
SP	0.585	0.441	0.170	0.494	0.159	0.403	0.413	

Table 8
Fornell Larcker results for assessment of discriminant validity.

	PAP	BLR	FP	HOB	PSC	PE	PP	SP	TP
PAP	0.762								
BLR	0.427	0.740							
FP	−0.247	−0.118	0.784						
BOB	0.428	0.631	−0.098	0.832					
PSC	−0.337	−0.143	0.182	−0.146	0.887				
PE	0.625	0.267	−0.177	0.275	−0.202	0.859			
PP	0.533	0.231	−0.099	0.258	−0.277	0.353	0.760		
SP	0.523	0.358	−0.158	0.437	−0.131	0.363	0.351	0.868	

determination (R^2) relays the level of variance that is explained by all constructs in relation to the outcome variable [176,301]. While general guidelines suggest R^2 values of 0.25, 0.50 and 0.75 correspond to weak, moderate, and substantial effect sizes [302], the measure is relative to the subject matter [230,231]. Accordingly, high R^2 values (i.e. > 0.75) are less probable when exploring new areas of social science research such as low-carbon energy acceptance [303,304]. Comparable to the DHAM ($R^2 = 0.669$) [76], the STEEEP Framework demonstrates moderate in-sample predictive power ($R^2 = 0.612$).⁴⁹

6.3.2. Out-of-sample predictive power

Evaluating out-of-sample predictive power helps establish the degree to which modelling results can inform strategic decision-making on hydrogen homes [166]. The PLS_{predict} tool developed Shmueli et al. [305] enables an initial assessment of in-sample predictive power in SmartPLS 4.1. The test calculates the Stone-Geisser's Q^2 value for the endogenous construct via a blindfolding procedure [306,307].⁵⁰ Q^2 measured 0.608 for perceived adoption potential, corresponding to

⁴⁹ Adjusted $R^2 = 0.610$.
⁵⁰ "A holdout-sample-based procedure that generates case-level predictions on an item or a construct level to reap the benefits of predictive model assessment in PLS-SEM [305]."

Table 9
Results of path analysis and hypothesis testing for the STEEEP Framework.

Hypothesis test	β -coefficient	95% bootstrap confidence intervals	p -value	f^2	Result
H1a: SP → (+) PAP	0.193	[0.155; 0.232]	<0.001	0.068 ^a	Accepted
H2a: BLR → (+) TP	0.474	[0.460; 0.480]	<0.001	n/a	Accepted
H3a: HOB → (+) TP	0.630	[0.614; 0.648]	<0.001	n/a	Accepted
H4a: TP → (+) PAP	0.179	[0.138; 0.219]	<0.001	0.063 ^a	Accepted
H5a: FP → (−) PAP	−0.082	[−0.113; −0.053]	<0.001	0.016	Accepted
H6a: PSC → (−) PAP	−0.126	[−0.155; −0.096]	<0.001	0.036 ^a	Accepted
H7a: PP → (+) PAP	0.241	[0.206; 0.276]	<0.001	0.116 ^a	Accepted
H8a: PE → (+) PAP	0.376	[0.338; 0.414]	<0.001	0.284 ^b	Accepted

SP = Safety Perceptions; BLR = Perceived Boiler Performance; HOB = Perceived Hob Performance; TP = Technology Perceptions; FP = Financial Perceptions; PSC = Perceived Socio-economic Costs; PP = Production Perceptions; PE = Positive Emotions; PAP = Perceived Adoption Potential.

^a Small effect size.
^b Moderate effect size.

strong predictive relevance (i.e. > 0.50) [82].⁵¹ Although PLS_{predict} facilitates a comparative assessment of out-of-sample predictive power, the procedure is not a statistical test [308].

In response, Liengard et al. [166] developed the cross-validated predictive ability test (CVPAT) to statistically compare the predictive capabilities of different models.⁵² The CVPAT indicates that the STEEEP Framework meets the minimum standard of predictive validity, since the model outperforms the indicator average (IA) prediction benchmark; whereby the average loss difference between the PLS-SEM model and the IA is negative, and significantly below zero [166]. Nevertheless, the proposed framework lacks strong predictive accuracy since it fails to outperform the more conservative linear model (LM) prediction benchmark [309], as reported in Table 10.

It may be concluded that the out-of-sample predictive capabilities of the STEEEP Framework are moderate. Integrating additional constructs into the model and fine-tuning the conceptual framework is required to raise predictive accuracy, in parallel to increasing explanatory power.

⁵¹ Results at the indicator levels were as follows: PAP1 = 0.315; PAP2 = 0.323; PAP3 = 0.327; PAP4 = 0.348; PAP5 = 0.380; PAP6 = 0.387. For the higher-order construct, Technology Perceptions (TP), the following values were reported: BLR1 = 0.425; BLR2 = 0.396; BLR3 = 0.355; BLR4 = 0.489; HOB1 = 0.615; HOB2 = 0.598; HOB3 = 0.538; HOB4 = 0.643.
⁵² The CVPAT performs "a pairwise comparison between theoretically derived competing models," and then selects "the model with the highest predictive power based on a prespecified statistical significance level" [166].

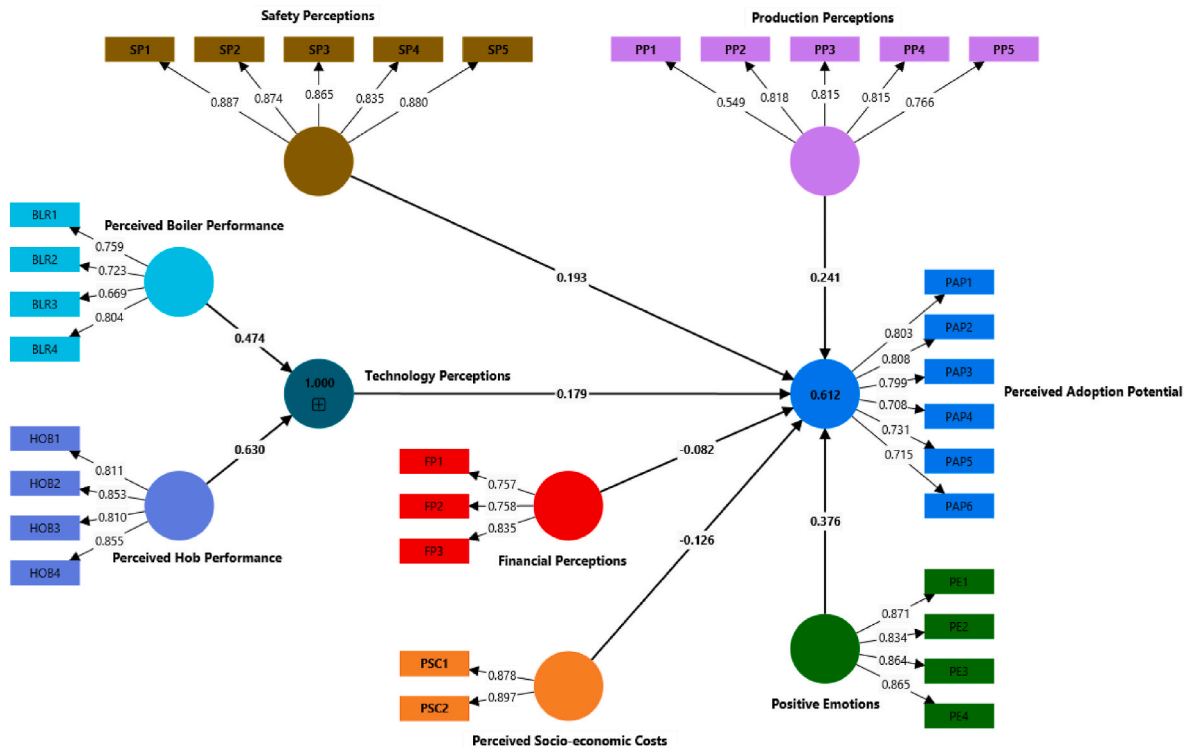


Fig. 8. Structural model path coefficients for the STEEP Framework.

Table 10
CVPAT benchmark and results for predictive ability test.

Target construct	PLS-SEM vs Indicator average (IA)				
	PLS loss	IA loss	Average loss difference	t-value	p-value
Perceived Adoption Potential	1.706	2.677	−0.971	18.998	<0.001
Technology Perceptions	2.970	5.969	−2.999	24.385	<0.001
Overall	2.428	4.558	−2.130	25.985	<0.001
	PLS-SEM vs Linear model (LM)				
	PLS loss	LM loss	Average loss difference	t-value	p-value
Perceived Adoption Potential	1.706	1.538	+0.168	9.262	<0.001
Technology Perceptions	2.970	0.000	+2.970	47.324	<0.001
Overall	2.428	0.659	+1.769	48.130	<0.001

This is reflected by the scope for also improving the predictive accuracy of technology perceptions as a higher-order construct (see Table 10).

6.4. Results for importance-performance map analysis

Following the structural model, effect size (i.e. importance) is largest for constructs positioned at the positive side of the matrix, namely, positive emotions, followed by production, safety, and technology perceptions. Positive emotions underperforms compared to the perceptual antecedents, which share similar latent variable scores. Consequently, strategic efforts should focus foremost on improving public perceptions around hydrogen production and safety to support favourable conditions for adopting domestic hydrogen (see Fig. 9).

At the negative end of the matrix, strategic measures should aim to neutralise the perceived socio-economic impacts of domestic hydrogen, whereas implementing measures to improve perceptions around financial costs is currently less of a priority. Furthermore, perceived socio-

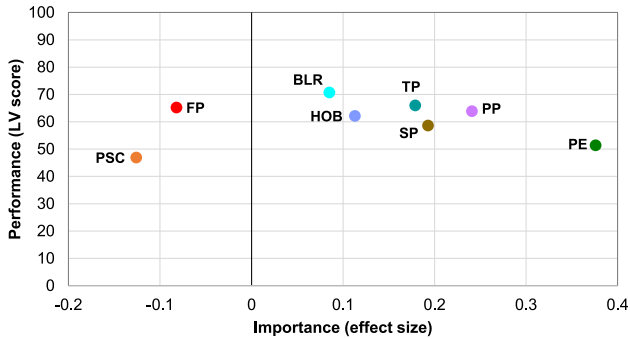


Fig. 9. Importance-performance map analysis for perceived adoption potential. Turquoise = Perceived Boiler Performance (BLR); Pale Blue = Perceived Hob Performance (HOB); Teal = Technology Perceptions (TP); Red = Financial Perceptions (FP); Orange = Perceived Socio-economic Costs (PSC); Brown = Safety Perceptions (SP); Purple = Production Perceptions (PP); Green = Positive Emotions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

economic costs is the lowest performing construct, yet equivalent to perceived hob performance in terms of importance (see SN16), which reinforces the strategic value of mitigating negative perceptions concerning fuel poverty and energy insecurity.

Consequently, from a sufficiency logic paradigm, the data suggests that increasing the perceived adoption potential of hydrogen homes may hinge primarily on increasing positive emotions, while improving production and safety perceptions, followed by diminishing perceived socio-economic costs. Thereafter, the next strategic priority action is to increase consumer expectations for hydrogen cooking (i.e. perceived hob performance), followed by mitigating negative financial perceptions, and finally, strengthening expectations for hydrogen heating (i.e. perceived boiler performance). However, the total effect of perceived relative advantage should be factored into decision-making, which sees

technology perceptions rank behind safety perceptions but ahead of perceived socio-economic costs (see Fig. 9). Additionally, observations regarding perceived boiler and hob performance as extracted via IMPA should be acknowledged but not overemphasised, since it is prudent to comprehensively evaluate direct effects on perceived adoption potential by adapting the STEEP Framework (see Section 6.6.2 and Section 6.7).

6.5. Moderating effects on perceived adoption potential

6.5.1. Simple slopes analysis

Moderating relationships were explored in SmartPLS 4.1 to extract more fine-grained insights regarding the antecedents of perceived adoption potential for hydrogen homes. The primary focus centred on testing whether gender, age, and housing tenure moderated specific relationships within the model, ahead of undertaking a targeted multi-group analysis. Age had a significant moderating effect on the respective relationships between financial perceptions, perceived socio-economic costs, positive emotions, and perceived adoption potential, as corroborated via simple slopes analysis (see Fig. 10). As summarised in Table 11, being older amplified the effect of negative financial perceptions and perceived socio-economic costs, but also strengthened positive emotions. Additionally, being male increased the positive effect of technology perceptions, while being female amplified the negative effect of perceived socio-economic costs, whereas gender had a negligible influence on financial perceptions (see SN17). Finally, mortgage owners proved more concerned about potential socio-economic costs from the transition to hydrogen homes than property owners, lending further support for H9a.

6.5.2. Insights from multigroup analysis

Following validation of the measurement model for each sub-sample (see SN18), the bootstrapping procedure (10000 sub-samples) was applied to statistically examine the proposed hypotheses (see Section 4.8) for each consumer sub-group (see SN19). For the main sub-sample ($N = 442$), the in-sample predictive power of the STEEP Framework proved moderate ($R^2 = 0.567$) with a corresponding Q^2 result of 0.549. However, the segmentation approach showed that the predictive capabilities of the model are significantly higher when tested on a group of male property owners aged 55 and over: $R^2 = 0.749$, $Q^2 = 0.723$. By comparison, there is significant scope to improve the predictive accuracy of the model when engaging with young, female mortgage owners ($R^2 = 0.436$, $Q^2 = 0.396$), as reflected in Fig. 11 and further quantified via the CVPAT (see Table 12).

Testing the STEEP Framework for the combined sub-sample sees one hypothesis rejected (H5a): Financial Perceptions $\rightarrow$ (–) Perceived Adoption Potential ($\beta = -0.023$, $p = 0.495$). All other relationships proved significant at $<0.1\%$, with positive emotions having the strongest effect ($f^2 = 0.224$), followed by production perceptions ($f^2 = 0.066$), safety perceptions ($f^2 = 0.063$), technology perceptions ($f^2 = 0.049$), and perceived socio-economic costs ($f^2 = 0.044$), as reported in SN19.

In a broad sense, findings at the sub-sample level align to the full sample since the sequence of effect sizes among constructs is retained, although financial perceptions becomes non-significant. However, upon closer inspection, it emerges that production perceptions and safety perceptions have similar effects on perceived adoption potential for the main sub-sample, whereas production perceptions is a more significant predictor across the full sample. Similarly, technology perceptions and perceived socio-economic costs have comparable positive and negative effects, whereas the influence of technology perceptions is higher across the main sample.

Considering results for the male and female sub-samples, greater degrees of divergence are observed between groups, and compared to the combined group and full sample. Financial perceptions remains consistent as a non-significant predictor of perceived adoption potential among each gender-based segment, reflecting the previous finding.

However, safety perceptions is also non-significant for the male sub-sample ($\beta = 0.034$, $p = 0.537$), while positive emotions remains the most influential predictor ($\beta = 0.463$, $p < 0.001$), followed by production perceptions ($\beta = 0.268$, $p < 0.001$) and technology perceptions ($\beta = 0.232$, $p < 0.001$), and lastly, perceived socio-economic costs ($\beta = 0.132$, $p = 0.001$).

Notably, in addition to financial perceptions, technology perceptions is non-significant for the female sub-group ($\beta = -0.011$, $p = 0.824$). Furthermore, safety perceptions has the strongest influence on perceived adoption potential ($\beta = 0.324$, $p < 0.001$), followed by positive emotions ($\beta = 0.241$, $p < 0.001$). Additionally, perceived socio-economic costs ($\beta = 0.181$, $p < 0.001$) has a marginally greater effect than production perceptions ($\beta = 0.166$, $p < 0.001$). These dynamics distinguish the female sub-group, since positive emotions followed by production perceptions emerge as the main antecedents of perceived adoption potential in all other cases. It follows that gender, age, and housing tenure correlate to distinct levels of perceptual and emotional antecedents of adoption potential for hydrogen homes, establishing strong support for H9a and H9b.

6.5.3. Analysis of group-specific differences

Given reliability constraints in comparing the statistical differences between path coefficients via PLS-MGA, a series of independent-samples Mann-Whitney U tests were performed to evaluate group-specific differences. Among the eight tests performed, two non-significant results were observed for perceived boiler performance and financial perceptions, as reported in Table 13.

The result is notable in further suggesting that financial perceptions are relatively homogenous across the population during the formative phase of the transition, as also observed when comparing the four consumer segments (i.e. MEG, VEG, FSG, and BLG) [154]. However, in other cases, the median ranks are significantly different, with the male sub-sample expressing more support for hydrogen production pathways, transmitting less concern about perceived socio-economic costs, while holding more favourable safety perceptions compared to the female sub-group (see SN19). It follows that the male sub-group has significantly stronger positive emotions about hydrogen homes ($p < 0.001$, $r = 0.250$), which contributes towards a higher level of perceived adoption potential (Males: $Md = 249$; Females: $Md = 206$),⁵³ as depicted in Fig. 12a.

At the indicator level, the two sub-groups were comparable regarding their willingness to adopt a hydrogen boiler before 2030 (Males: $M = 3.10$; Females: $M = 2.98$), and near identical in terms of perceiving social benefits from the domestic hydrogen transition ($M = 6.19$; $M = 6.17$). By contrast, male property owners were more willing to adopt a hydrogen hob before 2030 ($M = 3.14$) compared to female mortgage owners ($M = 2.85$), which contributed towards more support for hydrogen homes among the male sub-group (see Fig. 12a). Males also expressed stronger expectations for economic benefits ($M = 6.59$), and moreover, environmental benefits from hydrogen homes ($M = 7.64$). The discrepancy in levels of perceived environmental benefits between the two sub-groups can be partially explained by a stronger representation of male respondents with at least moderate levels of technology and environmental engagement, as reported in Fig. 3b.

The discrepancy underlying divergent perceptions for hydrogen hobs was further examined using the independent-samples Mann-Whitney U test. Reflecting the descriptive results (see Fig. 12b), perceptions of hydrogen hob efficiency were not significantly different between the sub-groups ($p = 0.463$, $r = 0.035$), which was also the case when considering smart performance ($p = 0.625$, $r = 0.030$). However, female mortgage owners aged 18–34 proved comparatively less optimistic

⁵³ Across the full sample, gender had a statistically significant effect on perceived adoption potential: $U = 390318$, $z = 2.544$, $p = 0.011$, $r = 0.059$; Males: $N = 810$, $Md = 958$, Females: $N = 1035$, $Md = 895$).

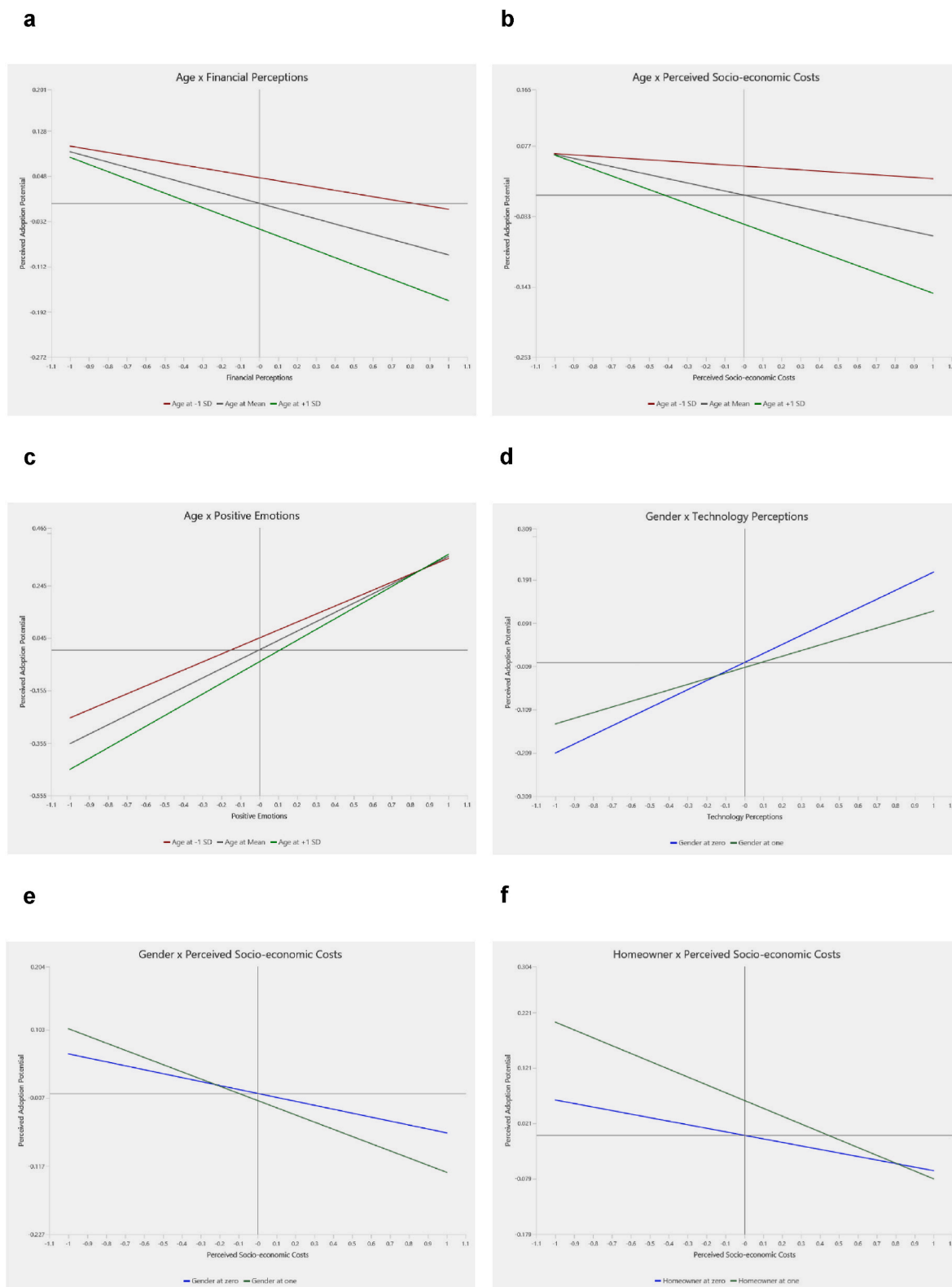


Fig. 10. Simple slopes analysis for moderating variables. (a) Age x FP → PAP (Red line = Younger; Green line = Older); (b) Age x PSC → PAP (Red line = Younger; Green line = Older); (c) Age x PE → PAP (Red line = Younger; Green line = Older); (d) Gender x TP → PAP (Blue line = Male; Green line = Female); (e) Gender x PSC → PAP (Blue line = Male; Green line = Female); (f) Homeowner x PSC → PAP (Blue line = Outright property owner; Green line = Mortgage owner). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 11
Results of path analysis for moderating variables.

Moderating relationship examined	β -coefficient (SD)	95% bootstrap confidence intervals	t-statistic	p-value	Pattern observed
Age x Financial Perceptions → Perceived Adoption Potential	−0.035 (0.017)	[−0.069; −0.001]	2.026	0.043	The negative effect of FP on PAP is strengthened as age increases
Age x Perceived Socio-economic Costs → Perceived Adoption Potential	−0.044 (0.017)	[0.078; −0.012]	2.625	0.009	The negative effect of PSC on PAP is strengthened as age increases
Age x Positive Emotions → Perceived Adoption Potential	0.053 (0.017)	[0.019; 0.085]	3.157	0.002	The positive effect of PE on PAP is strengthened as age increases
Gender x Technology Perceptions → Perceived Adoption Potential	−0.079 (0.033)	[−0.144; −0.016]	2.406	0.016	The positive effect of TP on PAP is stronger among males than females
Gender x Financial Perceptions → Perceived Adoption Potential	0.034 (0.032)	[−0.028; 0.096]	1.070	0.285	The negative effect of FP on PAP is not significantly influenced by gender
Gender x Perceived Socio-economic Costs → Perceived Adoption Potential	−0.052 (0.031)	[0.112; 0.008]	1.679	0.093	The negative effect of PSC on PAP is stronger among females than males
Homeowner x Perceived Socio-economic Costs → Perceived Adoption Potential	−0.078 (0.032)	[0.140; −0.016]	2.432	0.015	The negative effect of PSC on PAP is stronger among mortgage owners than outright property owners

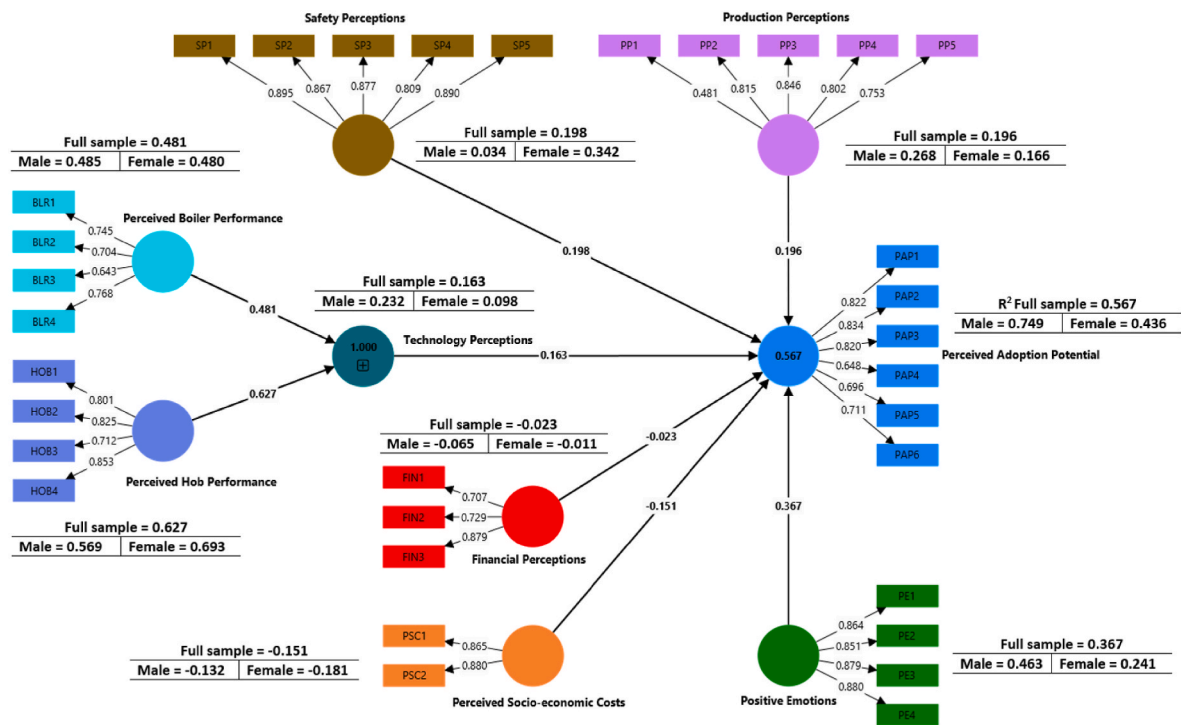


Fig. 11. Structural model path coefficients for sub-samples. Full sub-sample: N = 442; Male sub-sample: N = 160; Female sub-sample: N = 282.

Table 12
CVPAT benchmark and results for predictive ability test: Multigroup analysis.

PLS-SEM vs Indicator average (IA): STEEEP Framework					
Sub-sample population	PLS loss	IA loss	Average loss difference	t-value	p-value
Male (N = 160)	1.940	5.043	−3.103	8.079	<0.001
Female (N = 282)	2.953	4.180	−1.227	12.691	<0.001
Full sample (N = 442)	2.591	4.500	−1.908	12.309	<0.001
PLS-SEM vs Linear model (LM): STEEEP Framework					
Sub-sample population	PLS loss	LM loss	Average loss difference	t-value	p-value
Male (N = 160)	1.940	0.719	+1.221	11.523	<0.001
Female (N = 282)	2.953	0.883	+2.070	21.025	<0.001
Full sample (N = 442)	2.591	0.765	+1.826	24.017	<0.001

about the potential for better cooking control from hydrogen hobs ($Md = 213$) compared to male property owners aged 55 and older ($Md = 236$): $U = 20189$, $z = 1.862$, $p = 0.063$, $r = 0.089$. Moreover, consumer heterogeneity stemmed from male respondents anticipating that hydrogen hobs would be easier to maintain than gas hobs ($Md = 242$) as compared to female counterparts ($Md = 210$): $U = 19277$, $z = 2.569$, $p = 0.010$, $r = 0.122$.

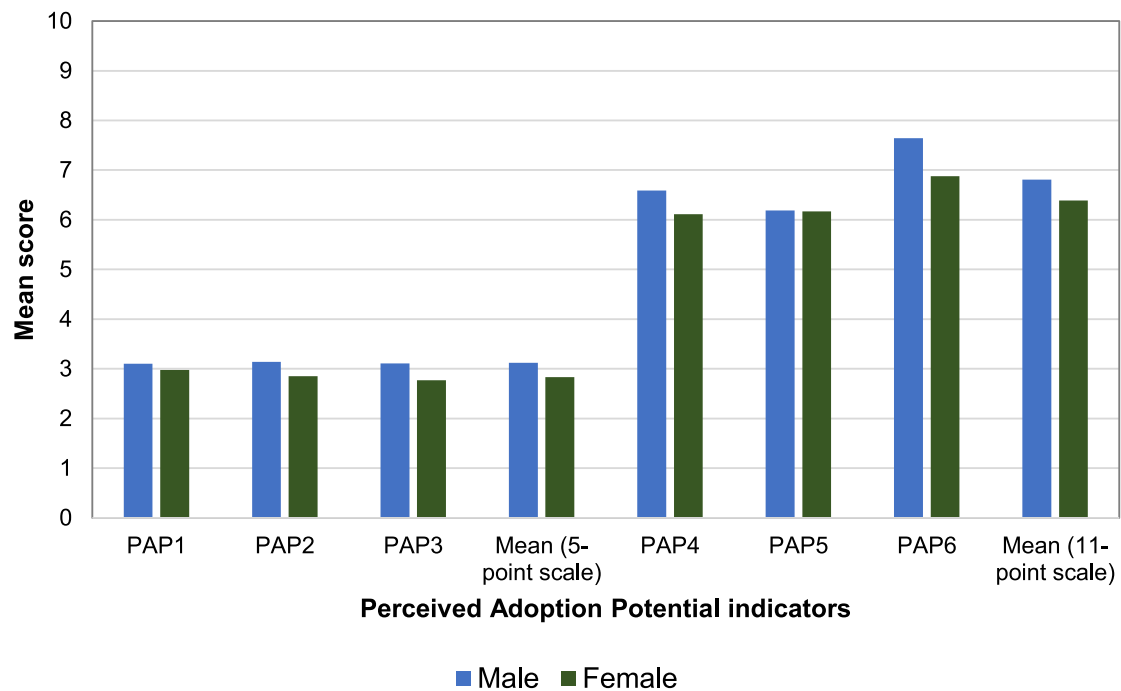
6.6. Results for necessary condition analysis

6.6.1. STEEEP framework with technology perceptions as a higher-order construct

Following the guidelines presented in Section 3.3.5, the CR-FDH line is applied to evaluate the necessary conditions for enabling perceived adoption potential for hydrogen homes (see Table 14). In parallel, the bottleneck tables show the level of antecedent constructs required to achieve specific levels of the target outcome (i.e. necessary conditions in degree) [83]. Table 15 shows the minimum values (rescaled to 0–100) that must be reached by each endogenous construct to manifest a certain

Table 13Independent Mann-Whitney *U* test comparing male and female sub-groups.

Construct	Mann-Whitney <i>U</i> value	Z-value	Male median rank	Female median rank	<i>p</i> -value (effect size)	Effect size (<i>r</i>)
Safety Perceptions	18978	−2.779	244	209	0.005**	−0.132
Perceived Boiler Performance	23357	0.618	217	224	0.536	0.029
Perceived Hob Performance	19876	−2.082	238	212	0.037*	−0.099
Financial Perceptions	22075	−0.38	225	220	0.704	−0.018
Perceived Socio-economic Costs	28367	4.584	185	242	<0.001***	0.218
Production Perceptions	13713	−6.861	277	190	<0.001***	0.326
Positive Emotions	15823	−5.252	264	198	<0.001***	0.250
Perceived Adoption Potential	18137	−3.431	249	206	<0.001***	0.163

**Fig. 12a.** Descriptive results for perceived adoption potential for male and female sub-groups.

level of perceived adoption potential. As summarised in Table 16, financial perceptions and perceived socio-economic costs are not necessary conditions, since both factors are negative predictors (see Fig. 8). Consequently, both factors are omitted from the bottleneck table [204]. In addition to Fig. 13a–d, the NCA charts illustrating the absence of a ceiling zone are provided in SN20.

According to the bottleneck analysis, reaching 20% of perceived adoption potential requires no minimum threshold for any predictor, while 30% calls for a minimum level of production perceptions. However, reaching 40–60% necessitates a minimum level of both production and safety perceptions. Subsequently, enabling 70% of perceived adoption potential also requires a minimum level of technology perceptions, while all predictors must meet a minimum threshold to manifest 80% of the target outcome (PE followed by PP, SP, and TP). Thus, to different degrees, multiple necessary conditions shape the feasibility of developing perceived adoption potential for hydrogen homes.

As perceived adoption potential increases, the failure rate of each construct shifts. At 80%, safety and technology perceptions share comparable failure rates, whereas technology perceptions retains a relatively low failure rate (2.7%), while positive emotions corresponds to the largest bottleneck (FR = 8.4%). However, in terms of manifesting 90% perceived adoption potential, there is a clear linear pattern whereby positive emotions remains the most significant bottleneck (FR = 33.23%), followed by production perceptions (FR = 19.4%),

technology perceptions (FR = 13.4%), and safety perceptions (FR = 9.5%).

It follows that each factor may be considered as a prerequisite for supporting the target outcome. In practical terms, this would translate to the following set of conditions for supporting deployment prospects for hydrogen homes: (1) early adopters should consider hydrogen to be at least marginally safer than natural gas; (2) early adopters should perceive hydrogen boilers and hobs to possess a distinct relative advantage over natural gas appliances; (3) early adopters should have adequate support for hydrogen production methods vis-à-vis the twin-track approach; and (4) early adopters should feel sufficient positive emotions about the hydrogen boilers and hobs.

From a necessity perspective, the environmental dimension related to hydrogen production pathways is suggested to be the most critical factor for supporting perceived adoption potential ($d = 0.208$), while the safety dimension also appears relatively critical ($d = 0.139$). By contrast, the criticality of technology perceptions ($d = 0.114$) was less decisive when operationalising the STEEP Framework via a higher-order construct. Moreover, while positive emotions is the most influential construct from a sufficiency perspective, the analysis calls into question whether emotional drivers are essential for raising initial adoption prospects during the formative phase of the domestic hydrogen transition ($d = 0.103$). Should 70% perceived adoption potential prove adequate for supporting deployment prospects for hydrogen homes, it

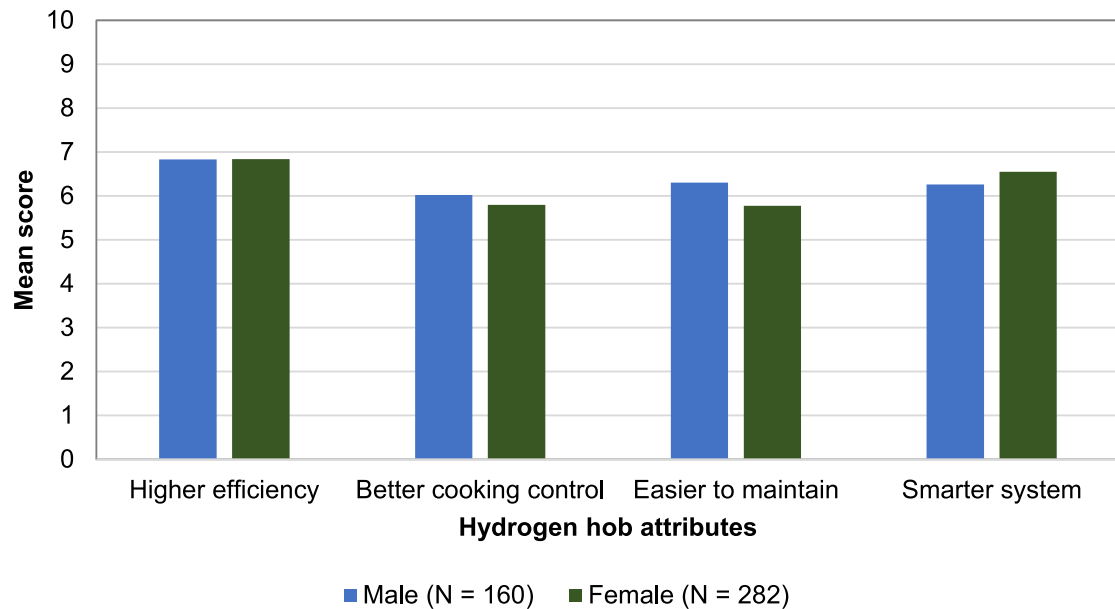


Fig. 12b. Consumer perceptions of hydrogen hob attributes (N = 442).

Table 14
Summary results of CR-FDH for the STEEP Framework.

Construct	Accuracy (%)	Slope	Intercept	Effect size	p-value
Safety Perceptions	99.566	1.488	36.156	0.139 ^a	<0.001
Technology Perceptions	99.404	0.461	67.518	0.114 ^a	<0.001
Financial Perceptions	100.00	n/a	n/a	0.000	<0.001
Perceived Socio-economic Costs	100.00	n/a	n/a	0.000	<0.001
Production Perceptions	99.350	1.352	22.946	0.208 ^a	<0.001
Positive Emotions	99.621	0.410	70.927	0.103 ^a	<0.001

^a Medium effect size and statistically significant.

may be the case that a lack of positive emotions could be compensated for by favourable environmental and safety perspectives, alongside other unidentified dimensions. However, at more ambitious levels of the target outcome, multiple necessary conditions need to be accounted for, with positive emotions becoming increasingly essential.

Regarding technology perceptions towards hydrogen boilers and hobs, Table 17 provides the summary of both ceiling line results,

confirming that the effect sizes are comparable in each case (i.e. for CE-FDH and CR-FDH). As stated in Section 3.3.5, the CE-FDH is selected in this case to account for a greater number of observations above the ceiling zone. The result shows that the larger effect size between the two lower-order constructs corresponds to perceived boiler performance ($d = 0.335$).

Table 18 presents the bottleneck table results for perceived boiler and hob performance, demonstrating that at a moderate level of perceived relative advantage (i.e. 60%), 9.5% of 8.5% of respondents fail to meet the required threshold, respectively. However, at the 70% threshold, there is more divergence between the two constructs, with 17.5% of respondents falling short of the required response for perceived hob performance (Likert scale score = 4.72), whereas boiler performance increases marginally to 10.6% (Likert scale score = 5.00).

The most significant discrepancy between perceived boiler and hob performance is observed in relation to securing 80% of the target outcome (i.e. technology perceptions), whereby more than twice as many respondents were unable to meet the minimum response level for perceived hob performance (54.3%) compared to boiler performance (25.3%). Additionally, the 90% level of technology perceptions/perceived relative advantage went unmet by 84.4% and 65.0% of respondents for hob and boiler performance, respectively.

Table 15
Bottleneck tables for perceived adoption potential.

Rescaled Latent variable scores (0–100)					Percentage (%)				
PAP (score)	SP (H1b)	TP (H4b)	PP (H7b)	PE (H8b)	PAP (%)	SP (H1b)	TP (H4b)	PP (H7b)	PE (H8b)
0	NN ^a	NN	NN	NN	0	0	0	0	0
10	NN	NN	NN	NN	10	0	0	0	0
20	NN	NN	NN	NN	20	0	0	0	0
30	NN	NN	5.215	NN	30	0	0	0.054	0
40	2.584	NN	12.609	NN	40	0.054	0	0.108	0
50	9.306	NN	20.003	NN	50	0.379	0	0.434	0
60	16.028	NN	27.397	NN	60	1.572	0	1.355	0
70	22.750	5.381	34.791	NN	70	3.577	0.650	2.873	0
80	29.472	27.067	42.185	22.150	80	5.908	2.764	6.775	8.347
90	36.195	48.753	49.579	46.564	90	9.539	13.388	19.458	33.225
100	42.917	70.439	56.973	70.977	100	15.014	57.344	33.930	83.523

PAP = Perceived Adoption Potential; SP = Safety Perceptions; TP = Technology Perceptions; PP = Production Perceptions; PE = Positive Emotions.

^a NN = Not a necessary condition.

Table 16
Results for combined use of PLS-SEM and NCA for perceived adoption potential (STEEP Framework).

Construct	PLS-SEM results (path coefficient; <i>p</i> -value)	NCA results (<i>d</i> ; <i>p</i> -value)	Combined result
Safety Perceptions	H1a: 0.193; <0.001	H1b: 0.139; <0.001	Significant determinant and a necessary condition
Technology Perceptions	H4a: 0.179; <0.001	H4b: 0.114; <0.001	Significant determinant and a necessary condition
Financial Perceptions	H5a: −0.082; <0.001	H5b: <0.001; <0.001	Significant determinant but not a necessary condition
Perceived Socio-economic Costs	H6a: −0.126; <0.001	H6b: <0.001; <0.001	Significant determinant but not a necessary condition
Production Perceptions	H7a: 0.241; <0.001	H7b: 0.208; <0.001	Significant determinant and a necessary condition
Positive Emotions	H8a: 0.376; <0.001	H8b: 0.103; <0.001	Significant determinant and a necessary condition

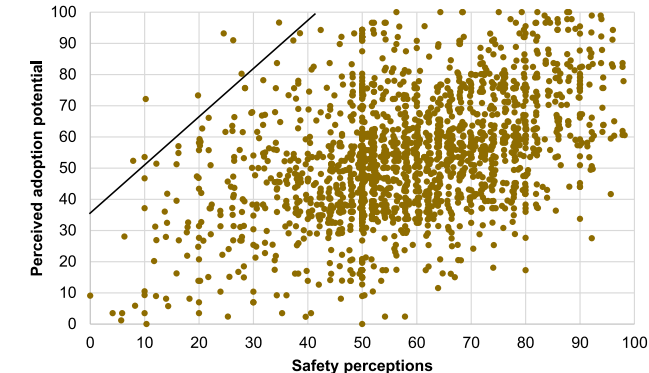


Fig. 13a. NCA scatterplot for safety perceptions as a predictor of perceived adoption potential (CR-FDH line).

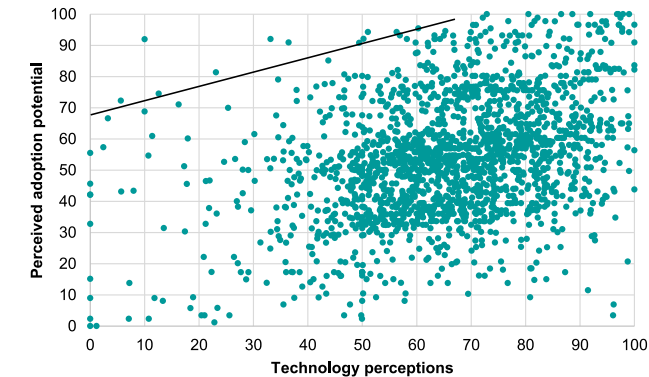


Fig. 13b. NCA scatterplot for technology perceptions as a predictor of perceived adoption potential (CR-FDH line).

As summarised in Table 19, both lower-order constructs are significant determinants and necessary conditions for enabling a perceived relative advantage. In practical terms, the data infers that increasing perceptions of both boiler and hob performance would have a combined effect of strengthening positive technology perceptions about hydrogen

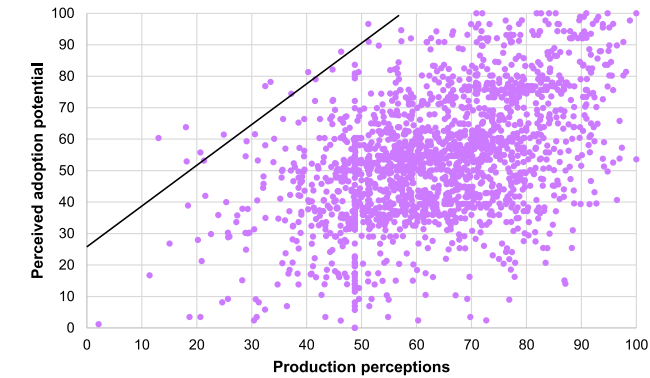


Fig. 13c. NCA scatterplot for production perceptions as a predictor of perceived adoption potential (CR-FDH line).

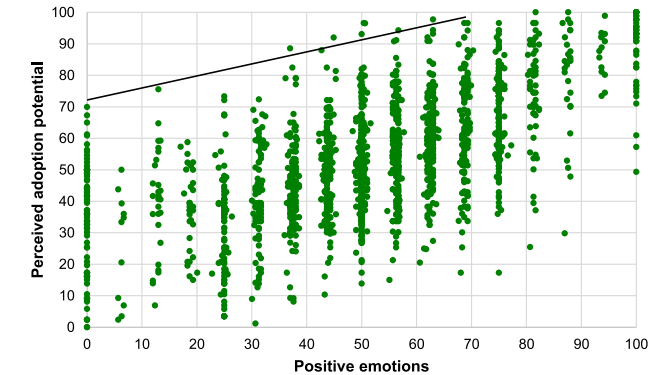


Fig. 13d. NCA scatterplot for positive emotions as a predictor of perceived adoption potential (CR-FDH line).

Table 17
Summary of ceiling lines results for technology perceptions as a higher-order construct.

Construct	CE-FDH			CR-FDH	
	Accuracy (%)	Slope	Intercept	Effect size (<i>p</i> -value)	Effect size (<i>p</i> -value)
Perceived Boiler Performance	97.832	0.834	2.193	0.335 ^a (<0.001)	0.366 ^a (<0.001)
Perceived Hob Performance	97.127	0.650	3.689	0.315 ^a (<0.001)	0.306 ^a (<0.001)

^a Large effect size and statistically significant.

Table 18
Bottleneck tables for technology perceptions using CE-FDH.

Likert-scale scores			Percentages		
TP (score)	BLR (H2b)	HOB (H3b)	TP (%)	BLR (H2b)	HOB (H3b)
0	NN ^a	NN	0	0	0
1	0.270	NN	10	0.542	0
2	0.270	NN	20	0.542	0
3	0.270	0.989	30	0.542	1.897
4	1.976	1.264	40	1.518	2.710
5	1.976	1.264	50	1.518	2.710
6	4.829	3.536	60	9.485	8.455
7	5.000	4.721	70	10.569	17.507
8	5.946	6.498	80	25.312	54.255
9	7.961	8.231	90	64.986	84.390
10	10.000	10.000	100	95.881	98.049

^a NN = Not a necessary condition.

Table 19

Summary of results for combined use of PLS-SEM and NCA for technology perceptions.

Construct	PLS-SEM results (path coefficient; <i>p</i> -value)	NCA results (<i>d</i> ; <i>p</i> -value)	Result
Perceived Boiler Performance	H2a: 0.474; <0.001	H2b: 0.335; <0.001	Significant determinant and a necessary condition
Perceived Hob Performance	H3a: 0.631; <0.001	H3b: 0.315; <0.001	Significant determinant and a necessary condition

homes, but each construct needs to reach certain minimum levels to enable perceived adoption potential. Nevertheless, when operationalising a higher-order construct, perceived boiler performance emerges as a more critical initial bottleneck for enabling positive technology perceptions (see Fig. 14a and b).

6.6.2. Adapted STEEEP framework: technology perceptions as a decomposed construct

The main motivation for operationalising an alternative version of the STEEEP framework is to test the direct effects of perceived boiler performance (H2c) and hob performance (H3c) on adoption potential for hydrogen homes. Ahead of performing NCA, the measurement model was validated (see SN21) and the bootstrapping procedure (10000 subsamples) was applied in SmartPLS 4.1 to examine the structural relationships of the adapted STEEEP Framework (see Fig. 15 and SN22).

Table 20 shows that consumer expectations for boiler performance ($t = 6.486$, $f^2 = 0.026$) has a stronger influence on shaping perceived adoption potential than hob performance ($t = 3.165$, $f^2 = 0.002$), which presents a contradictory finding to Fig. 9 (see Table 9). It emerges that the strategic priority for supporting perceived technology adoption potential likely rests with improving perceptions of boiler performance, as opposed to hob performance.

Operationalising technology perceptions as a decomposed construct via the adapted STEEEP Framework has a negligible effect on other constructs in the model (i.e. SP, FP, PSC, PP, and PE). While the model retains a moderate level of out-of-sample predictive power ($Q^2 = 0.609$) as gauged via the CVPAT for the indicator average (average loss difference = -0.971 , $t = 18.998$), the predictive capabilities of the STEEEP Framework are superior (see Table 10), which supports the rationale of modelling a higher-order construct [310].

6.6.3. Results from necessary condition analysis for the adapted STEEEP framework

The CR-FDH line is applied to perform NCA for the adapted STEEEP Framework as displayed in Table 21. The bottleneck tables⁵⁴ show that up to the 60% level of perceived adoption potential, neither perceived boiler nor hob performance are necessary conditions, whereas both constructs become critical for enabling 90% of the target outcome. At the 70% and 80% levels, a certain minimum level of boiler performance is required but the failure rate is negligible (i.e. < 2.8%). However, the dynamics between maximising perceived adoption potential or reaching 90% are significantly different.

At the 90% level, 16.6% of respondents failed to meet the threshold response for perceived boiler performance (Likert-scale score = 5.29), compared to 3.4% for perceived hob performance (Likert-scale score = 1.82). By contrast, 55.6% and 34.0% of respondents had a lower score for perceived boiler and hob performance, respectively, than required for maximising perceived adoption potential (see Table 22). From a practical perspective, there is limited feasibility of reaching a maximum

level for either perceived boiler or hob performance across segments of the population, however, there may be scope to secure 90% perceived adoption potential instead of a less ambitious target outcome.

Table 23 summarises the results for combined PLS-SEM and NCA vis-à-vis the adapted STEEEP Framework. The analysis provides a direct means to answer hypotheses H2d and H3d. Critically, evidence suggests that hydrogen heating and hydrogen cooking may diverge in their prospective roles in enabling perceived adoption potential for hydrogen homes (see as reflected in Fig. 16a and b): a perceived relative advantage associated with boiler performance is both a should-have and a must-have factor ($d = 0.126$, $p < 0.001$), whereas hob performance is a should-have factor but non-essential for the target outcome ($d = 0.041$, $p = 0.021$). It is suggested that the absence of specific levels of perceived hob performance may not necessarily constrain the perceived adoption level of hydrogen homes among UK consumers at this stage of the transition.

Potential support for this divergence is evident in the breakdown of descriptive statistics reported in Fig. 7a, which shows higher support levels for hydrogen boilers than hydrogen hobs across various attributes. To demarcate between each aspect underlying the perceived performance of hydrogen boilers and hobs, Fig. 17 provides a comparative assessment, wherein hydrogen heating outperforms cooking across each metric. It follows that consumers are more supportive of prospects for hydrogen heating compared to hydrogen cooking, with hydrogen boilers also emerging as the more critical technology to facilitating adoption potential.

6.6.4. Comparative insights from necessary condition analysis

Following the multigroup exploratory analysis conducted in Section 6.5, empirical insights from a necessity-based perspective are compared between the main sample and corresponding sub-groups. The results highlight clear instances and degrees of divergence when accounting for moderating variables, as captured in Table 24.

For the sub-group of male property owners aged 55 and over, multiple necessary conditions dictate the feasibility of enabling high levels of perceived adoption potential, with the production perceptions emerging as the foremost bottleneck ($d = 0.291$, $p < 0.001$), followed by safety perceptions, positive emotions, and technology perceptions. It stands to reason that higher levels of technology and environmental engagement among the sub-group partially explain the observed dynamics. Furthermore, when operationalising the adapted STEEEP Framework, both perceived boiler and hob performance correspond to prerequisite factors, with more weight on hydrogen heating ($d = 0.199$, $p = 0.014$). Comparable dynamics fail to be observed for the female sub-group since safety perceptions emerges as the sole necessary condition ($d = 0.158$, $p = 0.001$). Consequently, both sub-groups diverge to different extents compared to findings at the full sample level (see Table 24).

Finally, Table 25 summarises the findings at the sub-sample level from the complementary perspective of PLS-SEM and NCA. The results further emphasise that perceived hob performance is a non-critical predictor, whereas safety perceptions is a prerequisite in all cases. Additionally, it is notable that safety perceptions is non-significant for the male sub-group from an additive sufficiency perspective ($\beta = 0.034$; $p = 0.003$) but is nevertheless a precondition for enabling perceived adoption potential. By expanding the empirical lens to the multigroup level, Table 25 illustrates the presence of all PLS-NCA scenarios depicted in Fig. 5, underscoring the presence of heterogeneous preferences and preconditions for deploying hydrogen homes [154,228].

6.7. Results from combined importance-performance map analysis

The results from Figs. 8 and 9, and Table 15 are integrated to produce a combined importance-performance map (cIMPA), which can assist in fine-tuning strategic recommendations beyond a traditional IMPA. The method is applied to consider 90% perceived adoption potential in

⁵⁴ Results are omitted for safety perceptions, production perceptions, and positive emotions since the values are unchanged.

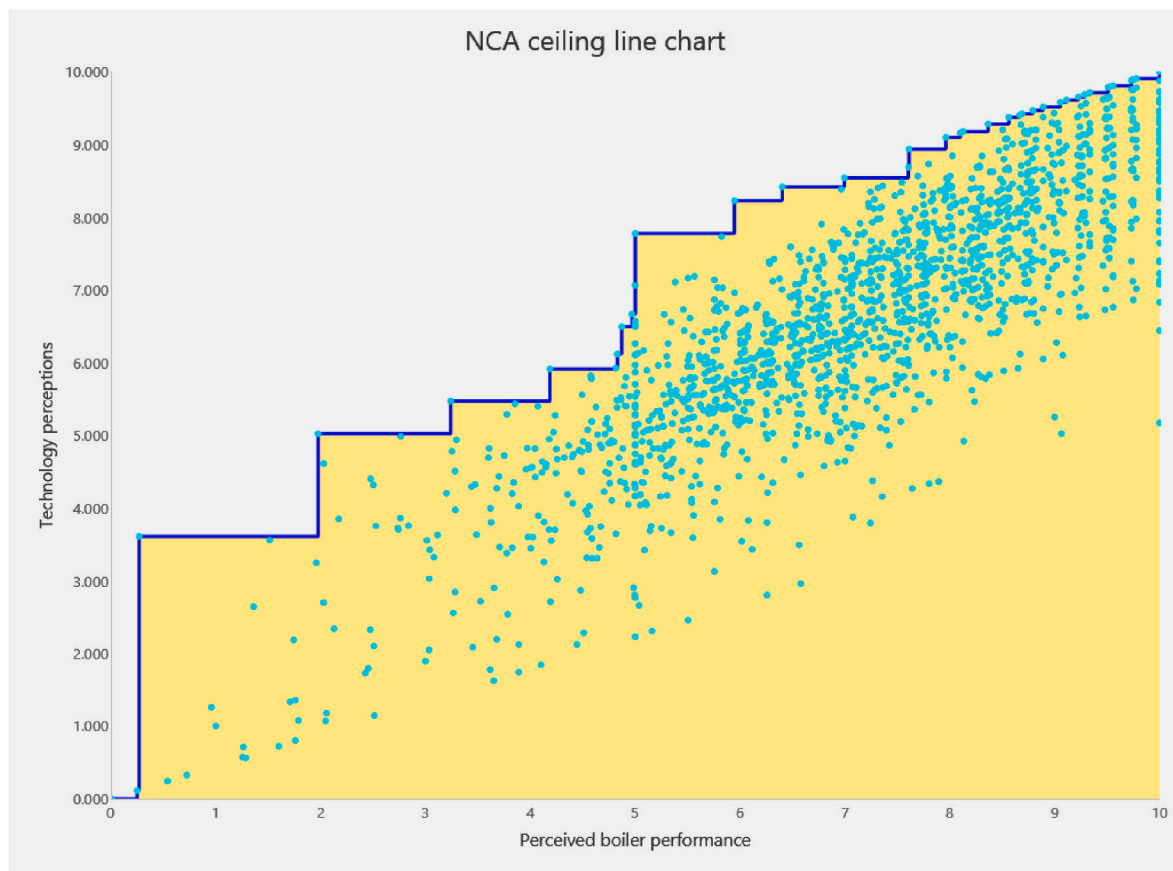


Fig. 14a. NCA scatterplot for perceived boiler performance as a predictor of perceived adoption potential (CE-FDH line).

Fig. 18a (see SN23 for 100% PAP).

In line with Fig. 9, the cIMPA shows that positive emotions is highly important but fails to outperform other constructs in the model. Accordingly, there is significant scope for improving the emotional dimension, which can likely be achieved by increasing the environmental perspective of hydrogen homes. Production perceptions demonstrates a medium-level performance but is more important than the safety or technological dimension in consolidating perceived adoption potential. Priority should be given to increasing public perceptions of blue and green hydrogen production pathways, and by proxy, the twin-track approach [43,131], since 19.5% of respondents were unable to achieve the required level for enabling 90% perceived adoption potential.

Although technology perceptions shares a medium-level performance, the construct is comparatively less important compared to production perceptions and safety perceptions. Nevertheless, improving technology perceptions should still be a strategic target, since it is a necessary condition as reflected by 13.4% of respondents falling short of the minimum threshold level. Lastly, safety perceptions is positioned between production and technology perceptions in terms of importance, while underperforming compared to both constructs. Although comparatively more respondents were able to meet the required threshold for facilitating 90% perceived adoption potential, Fig. 18a confirms that safety perceptions should not be overlooked in view of its classification as a necessary condition and significant scope for improvement in terms of performance.

The analysis is consolidated by extending the cIMPA results to the adapted STEEP Framework. Foremost, Fig. 18b demonstrates that for realising 90% perceived adoption potential, there is limited strategic value in targeting an improvement regarding perceptions of hydrogen hob performance since the construct is positioned in the bottom left

quadrant and few cases fail to meet the critical threshold ($FR = 3.4\%$). While prioritisation should be assigned to strengthening positive emotions, alongside consolidating production perceptions and to a lesser degree safety perceptions, the cIMPA shows that resources should also be allocated towards improving perceptions of boiler performance. Although the construct is positioned in the upper-left quadrant, 16.6% of respondents failed to meet the required threshold value. In addition to highlighting the divergence between heating and cooking, the cIMPA for the adapted STEEP Framework reinforces that technological perceptions may be less critical to perceived adoption potential at this stage of the transition than environmental and safety perspectives, alongside emotional responses to hydrogen homes.

Overall, the cIMPA reinforces the results from the initial IMPA (see Fig. 9), while supporting more fine-grained comparative insights by integrating information on the failure rate of each construct in achieving an ambitious target outcome of 90% perceived adoption potential. The principal finding is the clear-cut divergence between the strategic value associated with increasing perceived boiler performance as opposed to perceived hob performance.

To further demonstrate the analytical power of cIMPA, findings from the multigroup analysis are presented in Fig. 18c and d. The visualisations emphasise the degree to which two diametric groups of consumers may diverge when considering the parameters of the STEEP Framework. The relevance of perceived boiler performance is evident in the cIMPA for the male sub-group, but production perceptions is a more significant factor. However, both constructs have an above average performance. Strikingly, it is the emotional dimension which is influencing current bottleneck dynamics for perceived adoption potential among male property owners aged 55+ (see Fig. 18c). By contrast, improving the safety perspective of hydrogen is fundamental for raising perceived adoption potential among female mortgage owners 18–34

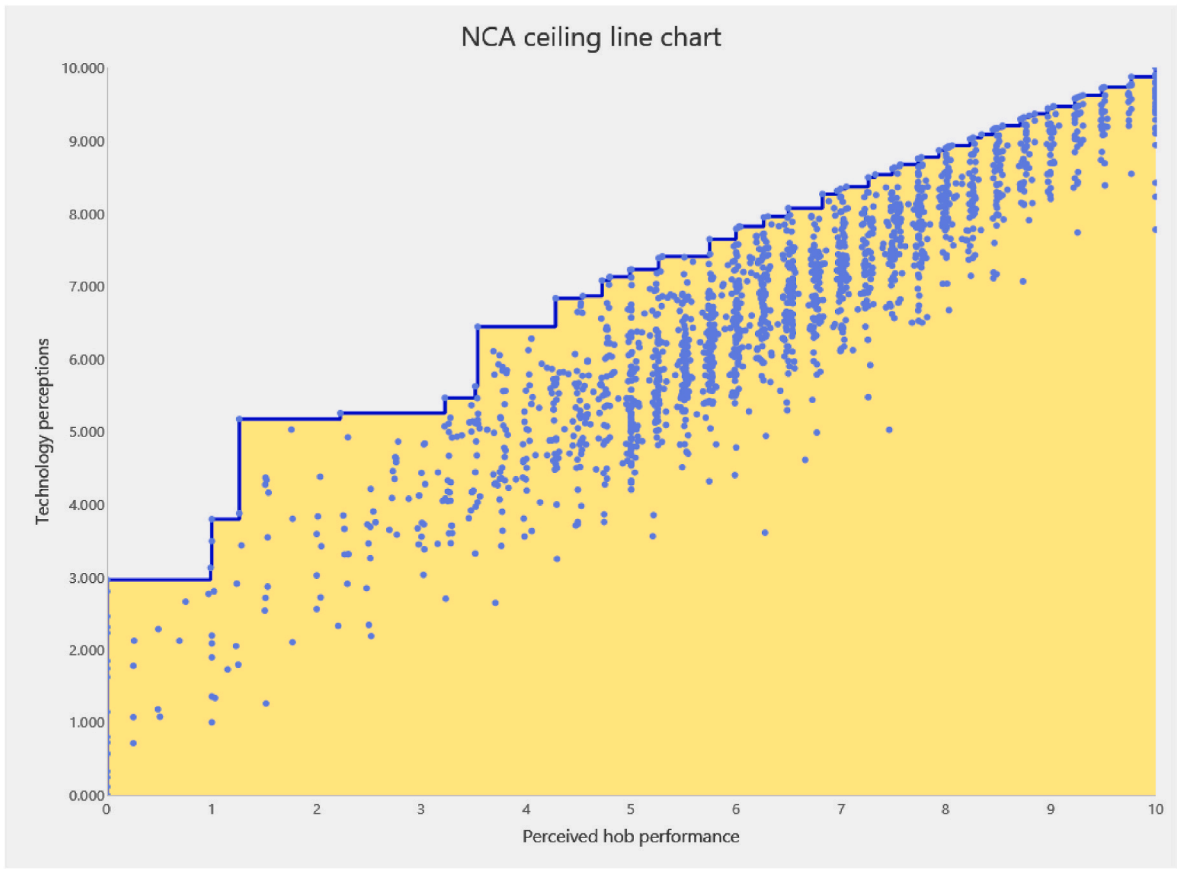


Fig. 14b. NCA scatterplot for perceived hob performance as a predictor of perceived adoption potential (CE-FDH line).

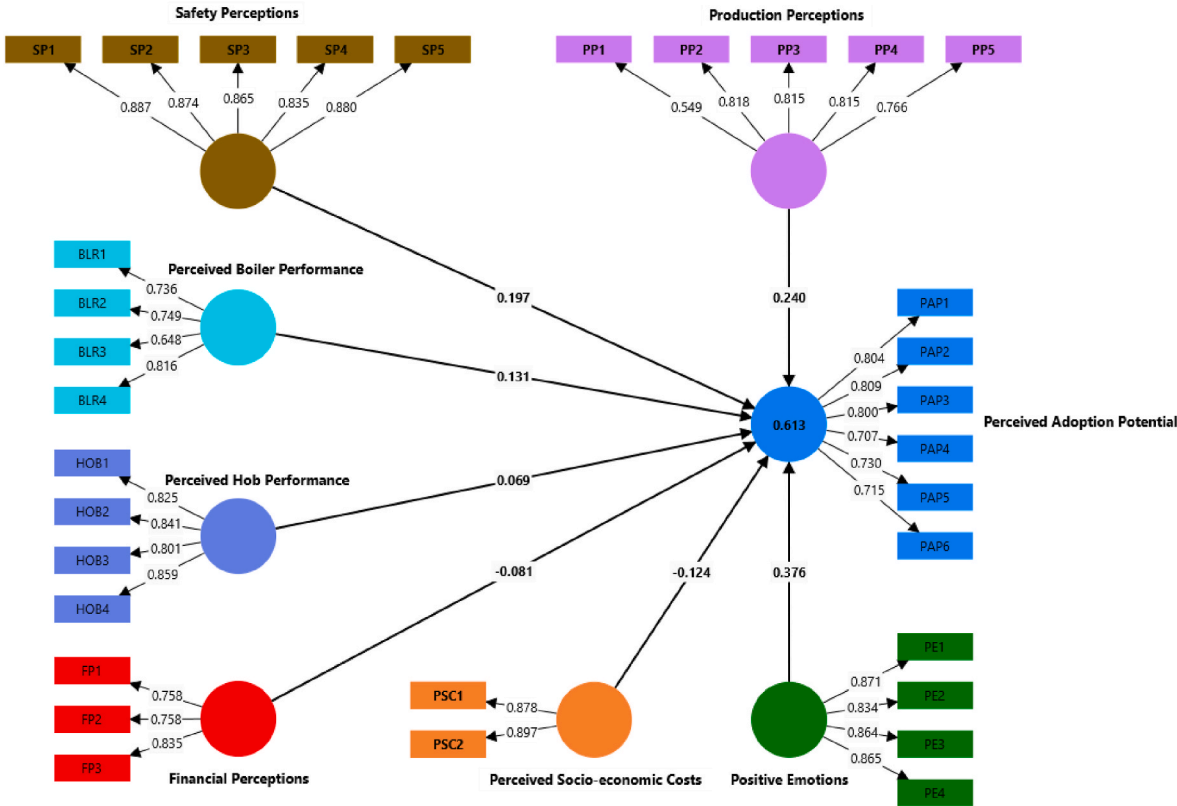


Fig. 15. Structural model path coefficients for the adapted STEEP Framework.

Table 20
Hypothesis test results for the Adapted STEEEP Framework.

Hypothesis	β -coefficient	95% bootstrap confidence intervals	ρ -value	f^2	Result
H1a: SP $\rightarrow$ (+) PAP	0.197	[0.157; 0.235]	<0.001	0.070 ^b	Accepted
H2c: BLR $\rightarrow$ (+) PAP	0.131	[0.093; 0.172]	<0.001	0.026 ^b	Accepted
H3c: HOB $\rightarrow$ (+) PAP	0.069	[0.026; 0.111]	0.002	0.007	Accepted
H4a: FP $\rightarrow$ (–) PAP	–0.081	[–0.111; –0.051]	<0.001	0.016	Accepted
H5a: PSC $\rightarrow$ (–) PAP	–0.124	[–0.153; –0.094]	<0.001	0.035 ^b	Accepted
H6a: PP $\rightarrow$ (+) PAP	0.240	[0.206; 0.275]	<0.001	0.115 ^a	Accepted
H7a: PE $\rightarrow$ (+) PAP	0.376	[0.338; 0.413]	<0.001	0.284 ^a	Accepted

^a Moderate effect size.
^b Small effect size.

Table 21
Summary of CR-FDH line results for the adapted STEEEP Framework.

Construct	Accuracy (%)	Slope	Intercept	Effect size	p -value
Perceived Boiler Performance	99.512	0.437	66.483	0.126 ^a	<0.001
Perceived Hob Performance	99.837	0.269	85.111	0.041	0.022

^a Medium effect size and statistically significant.

Table 22
Bottleneck tables for perceived adoption potential: Adapted STEEEP Framework.

Rescaled IMPA LV scores			Percentages		
PAP (score)	BLR (H2d)	HOB (H3d)	PAP (%)	BLR (H2d)	HOB (H3d)
0	NN ^a	NN	0	0	0
10	NN	NN	10	0	0
20	NN	NN	20	0	0
30	NN	NN	30	0	0
40	NN	NN	40	0	0
50	NN	NN	50	0	0
60	NN	NN	60	0	0
70	7.216	NN	70	0.650	0
80	30.073	NN	80	2.764	0
90	52.930	18.197	90	16.585	3.415
100	75.788	55.413	100	55.610	33.984

PAP = Perceived Adoption Potential; BLR = Perceived Boiler Performance; HOB = Perceived Hob Performance.

^a NN = Not a necessary condition.

Table 23
Summary of results for combined use of PLS-SEM and NCA for Adapted STEEP Framework.

Construct	PLS-SEM results (path coefficient; p -value)	NCA results (d ; p -value)	Result
Perceived Boiler Performance	H2c: 0.131; <0.001	H2d: 0.126; <0.001	Significant determinant and a necessary condition
Perceived Hob Performance	H3c: 0.069; 0.002	H3d: 0.041; 0.022	Significant determinant but not a necessary condition

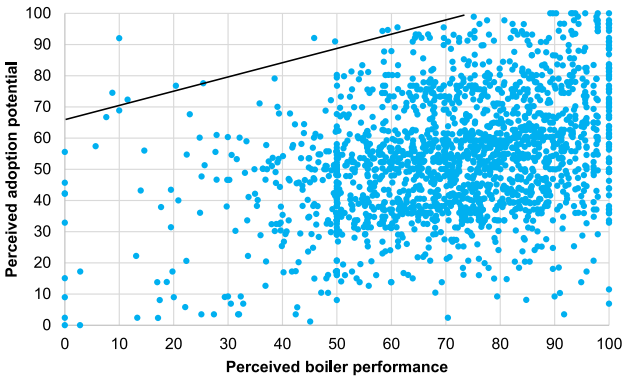


Fig. 16a. NCA scatterplot for perceived boiler performance as a predictor of perceived adoption potential (CR-FDH line).

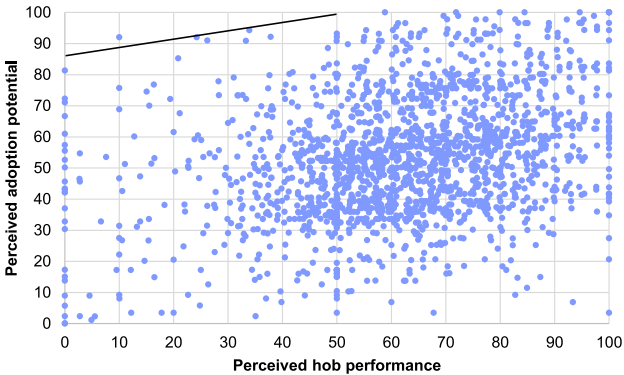


Fig. 16b. NCA scatterplot for perceived hob performance as a predictor of perceived adoption potential (CR-DH line).

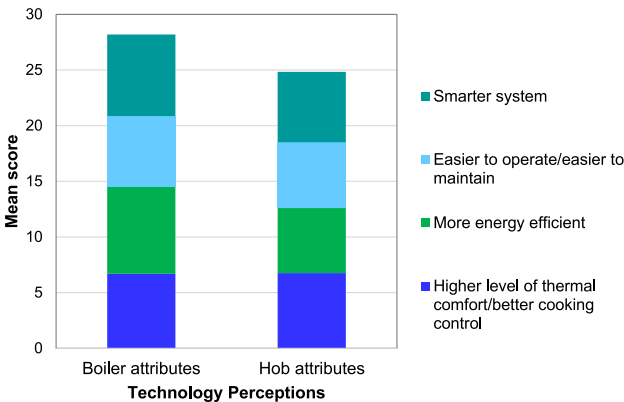


Fig. 17. Consumer perceptions of hydrogen boiler and hydrogen hob attributes (N = 1845).

years old (see Fig. 18d), which should assist in bolstering feelings of calm, confidence, satisfaction, and optimism.

7. Discussion

7.1. Practical contributions and policy implications

Through a novel multi-stage empirical approach, this study presents an extensive empirical evidence base for informing policy making efforts

Table 24
Summary of results from necessary condition analysis.

STEEEP Framework				
	Full sample (N = 1845)	Main sub- sample (N = 442)	Male sub- sample (N = 160)	Female sub- sample (N = 282)
Safety	0.139*	0.211*	0.246*	0.158*
Perceptions	(<0.001)	(<0.001)	(<0.001)	(0.001)
Technology	0.114*	0.152	0.162*	0.086
Perceptions	(<0.001)	(0.081)	(0.009)	(0.656)
Production	0.208*	0.169*	0.291*	0.149
Perceptions	(<0.001)	(0.002)	(<0.001)	(0.098)
Positive	0.103*	0.139*	0.174*	0.113
Emotions	(<0.001)	(<0.001)	(<0.001)	(0.090)
Adapted STEEEP Framework				
Perceived Boiler	0.126	0.191	0.199*	0.108
Performance	(<0.001)	(0.066)	(0.014)	(0.355)
Perceived Hob	0.041	0.108	0.112*	0.191
Performance	(0.022)	(0.059)	(0.013)	(0.188)

* Medium effect size and statistically significant.

Table 25
Summary of results from combined PLS-SEM and NCA across sub-samples.

Construct	Main sub-sample (N = 442)	Male sub-sample (N = 160)	Female sub-sample (N = 282)
Safety	Significant	Non-significant	Significant
Perceptions	determinant and a necessary condition	determinant but a necessary condition	determinant and a necessary condition
Technology	Significant	Significant	Non-significant
Perceptions	determinant but not a necessary condition	determinant and a necessary condition	determinant and not a necessary condition
Production	Significant	Significant	Significant
Perceptions	determinant and a necessary condition	determinant and a necessary condition	determinant but not a necessary condition
Positive	Significant	Significant	Significant
Emotions	determinant and a necessary condition	determinant and a necessary condition	determinant but not a necessary condition
Adapted STEEEP Framework			
Perceived Boiler	Significant	Significant	Non-significant
Performance	determinant but not a necessary condition	determinant and a necessary condition	determinant and not a necessary condition
Perceived Hob	Non-significant	Non-significant	Non-significant
Performance	determinant and not a necessary condition	determinant but a necessary condition	determinant and not a necessary condition

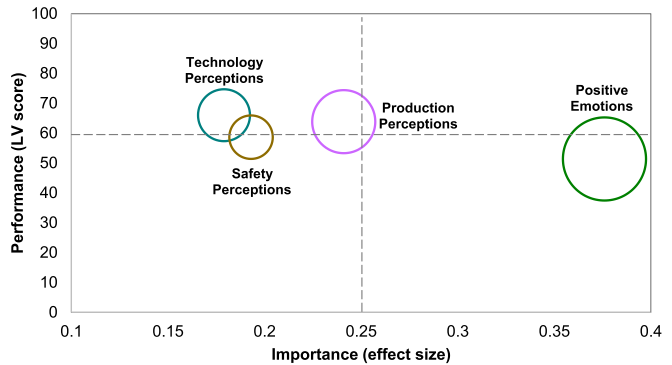


Fig. 18a. cIMPA for 90% perceived adoption potential (STEEEP Framework). Construct's average importance = 0.247. Constructs' average performance = 45.273. Bubble size = Percentage of cases that have not met the critical threshold.

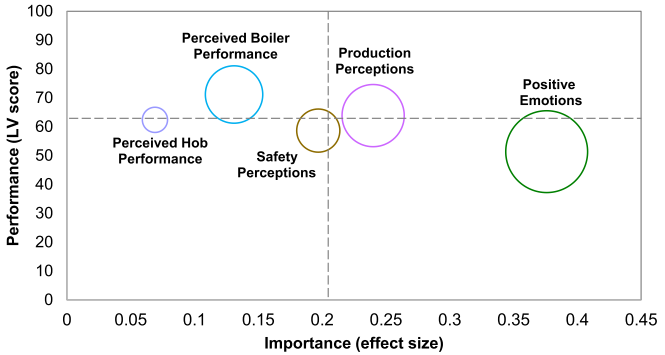


Fig. 18b. cIMPA for 90% perceived adoption potential (Adapted STEEEP Framework: Full sample). Construct's average importance = 0.203. Constructs' average performance = 40.684. Bubble size = Percentage of cases that have not met the critical threshold.

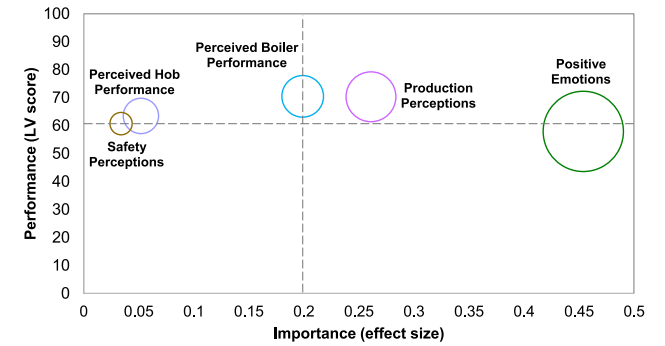


Fig. 18c. cIMPA for 90% perceived adoption potential (Adapted STEEEP Framework: Male sub-sample). Construct's average importance = 0.200. Constructs' average performance = 61.010. Bubble size = Percentage of cases that have not met the critical threshold.

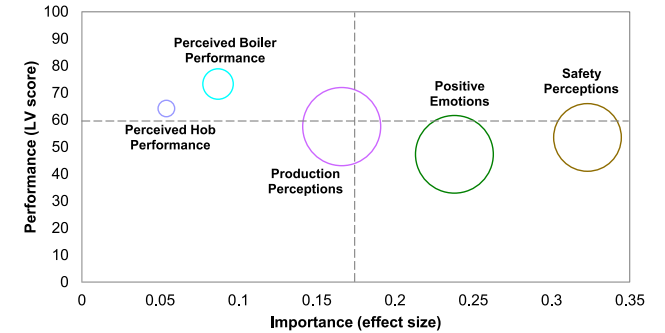


Fig. 18d. cIMPA for 90% perceived adoption potential (Adapted STEEEP Framework: Female sub-sample). Construct's average importance = 0.174. Constructs' average performance = 59.610. Bubble size = Percentage of cases that have not met the critical threshold.

and decision-making in the hydrogen landscape. Several practicalities should be kept in mind when considering potential implications. Multiple socio-technical barriers to realising domestic hydrogen futures will need to be overcome [19], with cost barriers and infrastructural challenges among the principal challenges to deploying hydrogen homes [311,312]. Moreover, while this study considered 100% hydrogen-fuelled appliances for domestic heating and cooking, the examined scenario is largely contingent on the feasibility of blending

hydrogen into the gas grid [49,242,313,314]. The level of capital investment required to move from gas blends to 100% hydrogen-fuelled pipelines is significant [36,315], which could potentially exacerbate the perceived socio-economic and financial costs of the transition for consumers [130,148].

In the residential context, the main motivation for switching the gas grid to hydrogen is emissions reduction from heating, while cooking may present somewhat of a low-hanging fruit. However, scarce attention has been allocated towards examining the potential dichotomy between low-carbon pathways for residential heating and cooking [41]. At present, it is somewhat presumed or otherwise anticipated that hydrogen cooking will ‘come along for the ride’ if the gas grid switches over, as reflected by a dual focus in prior consumer research [42,75]. A case in point is the UK Hydrogen Strategy [43], which makes just a handful of references to cooking, whereas heating receives over 400 mentions, emerging as the focal point of government-funded consumer research [137,243].

This study challenges existing assumptions to a degree, motivating key stakeholders to consider alternatives, namely, should hydrogen cooking be removed from the equation, actively promoted, or retain its status quo as the complementary technology underlying the very notion of a hydrogen home? From a climate change perspective, a range of technology adoptions for heating, including hybrid heat pumps [316],⁵⁵ warrant consideration [317]. However, emissions reduction from cooking cannot be argued as a strong motivating factor for converting the gas grid to hydrogen. Furthermore, unlike heat pumps which remain a niche technology in the UK context [235] despite ambitious targets [40], induction hobs already accounted for 24% of the UK market share for household cooking technologies in 2017 [318].⁵⁶

The growth dynamics⁵⁷ characterising the market for induction hobs partially reflect recent technological advances [319] and changing energy cultures [320], linked to growing awareness about energy efficiency and sustainable consumption [321–323]. However, most critically, purchasing an induction hob is much more economical compared to a heat pump, which remains an exorbitant investment for most UK households; reflecting a pronounced “eligibility-readiness gap” which is yet to be narrowed by available subsidy schemes [324].⁵⁸

Market dynamics dictate the strong likelihood of accelerated diffusion for induction hobs across the UK housing stock, which is on course to become the dominant technology, as witnessed for electric ovens [318]. This trajectory begs the question as to whether hydrogen cooking has a place in the UK’s energy future or should be reserved solely for exploration in the context of supporting universal access to clean cooking [325,326]. While this study cannot answer such a multi-faceted question, the presented consumer-oriented perspective presents food for thought.

From a sufficiency-based perspective, increasing the perceived performance of hydrogen hobs would raise adoption potential for hydrogen homes, however, there is limited strategic value in allocating resources to this end. By contrast, the adapted STEEEP Framework indicates that consumer perceptions regarding boiler performance will shape enabling conditions for the domestic hydrogen transition, in addition to having a more pronounced effect on underlying technology perceptions for hydrogen homes. Furthermore, multigroup analysis suggests female respondents are less optimistic about the cooking control and

maintenance aspects of hydrogen hobs than males (see Fig. 17), which could impede consumer support. From a safety perspective, hydrogen cooking also arouses stronger concerns than hydrogen heating [41,42].

Considering the presented evidence base, policy makers may reconsider the current heat-centric approach to residential decarbonisation. One possibility is to integrate more direct support for transitioning the cooking sector to electrical appliances as an interim measure. Removing cooking from the equation could help streamline decision-making on domestic hydrogen, with potential benefits for improving safety perceptions and risk management prospects, while easing the burden of future hydrogen supply chains. Ahead of policy decisions intended for 2026, consumer attitudes towards hydrogen heating, hydrogen cooking, and the combined notion of a hydrogen home should be examined by multiple research groups to address the relatively sparse comparative evidence base.

Technological and safety perspectives are paramount to adoption prospects for hydrogen homes and intrinsically linked to emotional response. Regarding emotions, this study aligns with previous findings, which report stronger positive feelings about gas-based energy futures among male respondents [105,245,263,272]. Moreover, when objective knowledge of hydrogen fuel is low and consumer experience absent, the emotional dimension plays a significant role in shaping perceived adoption potential. Evidence suggests older segments of the population are more at ease with the concept of hydrogen homes, while property ownership alongside technology and environmental engagement may increase the likelihood of positive emotions. The finding somewhat contradicts observed generational differences in climate-related emotions [267]. Younger demographics in the UK share stronger feelings of worry, fear, guilt, and outrage about climate change [267], which implies more support for low-carbon energy technologies. Further analysis is needed to demarcate between the effects of climate change engagement, technology awareness, and age in shaping emotional response to hydrogen homes.

This analysis suggests that in addition to being an imperative from a technical standpoint [12], consumer confidence in hydrogen safety is a prerequisite condition for deploying hydrogen homes. Notably, safety perceptions emerged as the sole necessary condition for enabling perceived adoption potential among the female sub-group, which was highly representative of multi-occupants (i.e. young families) living in a mortgage owned property. In parallel, the socio-political legitimacy of the domestic hydrogen transition will determine the feasibility of technology deployment.

The importance of perceived environmental value, in addition to socio-economic benefits [73,117], is reflected in the recent context of community resistance to hydrogen trials (see Section 4.5) and transmitted by the critical status of production perceptions in this study.⁵⁹ It follows that allocating resources towards improving hydrogen production perceptions is a recommended course of action for supporting the transition to hydrogen homes. In response, government representatives, gas distribution network operators, and other agents of the domestic hydrogen transition should foster public engagement in the industrial north, where hydrogen hubs are currently envisioned [327] in conjunction with CCS clusters [328].

7.2. Methodological and theoretical implications for future research

This study advances the emerging evidence base on the dynamics of social acceptance and adoption potential for hydrogen homes [42,76,115,154]. Drawing on the foundations of the unified theory of domestic hydrogen [77], the STEEEP Framework integrates five specific dimensions (safety, technological, economic, environmental, and emotional) to examine the necessary and sufficient conditions for establishing high levels of perceived adoption potential for hydrogen

⁵⁵ Combining an electrically-driven heat pump with a gas boiler, along with a dedicated controller [386].

⁵⁶ More up-to-date figures on the growth of the induction hob market could not be reliably sourced for reporting within this discussion.

⁵⁷ Compound annual growth rate (CAGR) forecasts for portable induction hobs in the UK (~6.6%) are comparable to other major economies such as the United States, Japan, China, and South Korea [387].

⁵⁸ Lamb and Elmes [324] quantify the technical and market readiness of UK households for adoption heat pumps as 34.7% and 11.1%, respectively.

⁵⁹ A necessary condition in all cases except for the female sub-group.

boilers and hobs.

Operationalising a hybrid construct composed of six measurement items, perceived adoption potential was gauged according to the subjective responses of UK property owners living in gas-fuelled homes. The integration of multiple consumer perspectives vis-à-vis the STEEP Framework aligns to other technology contexts such as internet use [329], the adoption of smartphones [330], electric cars [331,332], and electric motorcycles [217], in addition to residential energy use [333].

This study makes a novel contribution by integrating ideas and constructs from risk perceptions literature [334,335], diffusion of innovation theory [125], behavioural economics [336–338], environmental psychology [69,339,340], and affective models [341–344]; mirroring “the fresh theoretical approach” espoused by Al-Emran [345] vis-à-vis Technology-Environmental, Economic, and Social Sustainability Theory (T-EESST). By advancing conceptual thinking in the nascent context of hydrogen acceptance [73,94] through a multi-stage empirical approach (see Fig. 4), the analysis entails several theoretical and methodological implications for future research.

First and foremost, this research demonstrates the efficacy of combining PLS-SEM and NCA in conjunction with cIMPA to achieve more fine-grained analytical insights. Energy acceptance scholars should ground their efforts in comprehending technology cases through a complementary causal perspective by identifying necessary and sufficient factors underpinning prospective market deployment, uptake, and growth potential. While this study centred on willingness to adopt hydrogen technologies this decade, incorporating survey questions on adoption intention across additional timespans would yield opportunities to capture longitudinal insights regarding the innovation-decision process (see Fig. 1). This adaptation could enable researchers to leverage cIMPA for comparing the feasibility of target outcomes across different timelines according to observed bottleneck dynamics. As one of the derivatives of NCA [84,87,218,223], cIMPA constitutes an important methodological contribution to the literature [346], which should be rapidly adopted by the research community to consolidate strategic recommendations beyond the two-dimensional level of traditional IMPA.

Secondly, the integration of simple slopes analysis and multigroup analysis extends empirical insights beyond the aggregate sample level. Conclusions derived from data analysis that fails to account for potential consumer heterogeneity may prove incomplete [191,192], especially in the face of strong multigroup dynamics as described in Section 3.2.1. However, correlation between categorical variables (e.g. annual income or age and level of financial involvement in technology purchasing decisions) can present a challenge for demarcating significant moderating effects.

At present, it remains somewhat indeterminable whether the perceptions of respective male and female respondents living in multi-occupancy properties definitively captures attitudes at the household level [280].⁶⁰ Nevertheless, evidence suggests that males are more pro-hydrogen technology and less sensitive to potential economic risk factors than females. Similar trends have been observed in the German context, wherein middle-aged men with technical professions living in multi-person households proved more inclined to invest in electric vehicles than other potential adopter groups [347].

To circumvent limitations reflected in this study, subsequent consumer-oriented research can target larger and equivalent sample sizes for specific segments, thereby supporting opportunities to examine group-specific differences according to distinct socio-structural parameters (i.e. via PLS-MGA). Notably, there is a pressing need for further engagement with households from industrial/inner city areas (8.9% of

the sample), since the deployment of hydrogen homes is firmly anchored in the industrial north [36,73,253]. Critically, researchers should leverage the opportunity to employ up-to-date statistical procedures to support advanced multigroup analysis [154,193,348].

An important caveat during the filtering process is to clarify whether a given respondent self-defines as full or partial agent in the overall decision-making process for adopting hydrogen homes. This study approximated the highlighted direction by employing financial involvement as a categorical filter, however, non-economic factors will also shape household decisions especially when considering a family-oriented technology like domestic cooking [41,42]. In the domain of kitchen-related practices, socio-cultural and lifestyle factors may prove pertinent to shaping technology preferences for cooking technologies [41,42].

Thirdly, the analysis reveals important dynamics concerning the treatment and influence of higher-order constructs. Adapting the STEEP Framework by decomposing technology perceptions into its respective antecedents (perceived boiler and hob performance), counteracted the risk of drawing artificial conclusions from the study. Thus, it is advisable to decompose lower order constructs when exploring new models, which may justify comparative analyses such as undertaken within this study, or otherwise provide a robustness check for reporting in supplementary materials. For example, adjusting to the given national context [141,257,349], researchers can explore perceptions for different hydrogen production pathways by integrating additional measurement items to form valid constructs for comparative assessment, in addition to a more comprehensive higher-order construct.

Fourthly, in view of partially sporadic support levels for the twin-track approach (see Table 5 and Fig. 7a), there is strong motivation to fine-tune survey instruments going forward. It may be the case that respondents consider a two-dimensional timeline as somewhat arbitrary and need clearer contextual information accompanied by more explicit levels of temporal demarcation. Examining hydrogen production perceptions across different time horizons such as the remainder of this decade, 2030–2040, and 2040–2050 could increase the reliability and granularity of findings in the net-zero context [43,350].

In response, scholars should aim to extend the evidence base on the hydrogen economy by further comparing public perceptions of different hydrogen production pathways and energy technologies [8,136,349]. At the same time, there is a growing imperative to compare public perceptions of different residential decarbonisation pathways in national contexts such as the UK, as recently highlighted by Becker et al. [351] and Thomas et al. [148]. A starting point is to build on the initial contribution of Williams et al. [137] through a more systematic analysis of domestic hydrogen and heat pumps.

Finally, the influence of knowledge and awareness should be acutely explored. This study attests to the low baseline level of objective knowledge (see Table 4), while the DHAM suggests cognitive processes may be relatively insignificant to social acceptance during the pre-deployment stage of hydrogen heating and cooking technologies [76]. However, parallel evidence from this dataset identified a ‘knowledge deficit’ as a primary explanatory factor of divergent consumer attitudes towards hydrogen homes [228]. Since knowledge plays a more decisive role as consumers move through the innovation-decision process [125, 352,353], it is reasonable to anticipate that the inclusion of cognitive factors would further explain perceived adoption potential. In response, researchers should thoroughly consider the implications of selected information provision materials during the survey design phase and apply explicit measures to test the effects of coloured information [139–141, 258].⁶¹

Although hydrogen studies have explored the effect of information

⁶⁰ Across the full sample, households with three or more occupants ($Md = 939$) had more positive perceptions than households with two occupants ($Md = 921$), and moreover single occupiers ($Md = 834$): $H(2, N = 1845) = 6.206, p = 0.045$.

⁶¹ Bearing in mind that the acquisition of technical knowledge does not necessarily translate into behavioural change in the context of environmental practices [388] such as household energy consumption [389].

provision using survey data [75,140,141], qualitative methods such as deliberative workshops and semi-structured interviews can provide additional research perspectives, as demonstrated by Fylan and colleagues [138] in the context of the H21 Leeds City Gate Project [354]. Qualitative approaches are a critical means for advancing the use of PLS-SEM [88], while also offering a range of advantages over quantitative methods when considered in isolation [355,356]. Deliberative workshops may afford more streamlined opportunities to apply different methods of information provision [357,358] such as positive, neutral, and negative framings around the domestic hydrogen transition [75].

8. Conclusions

This study reflects the notion that “understanding and coordinating the linkages between transition schemes and social factors and constraints are of vital importance” to the decarbonisation agenda and trajectory of the hydrogen transition [317]. As a starting point, this analysis identified essentially one-dimensional dynamics when examining domestic hydrogen acceptance through the complementary perspective of PLS-SEM and NCA, with three constructs (perceived community benefits, production perceptions, and safety perceptions) corresponding to significant determinants and necessary conditions.

Through the lens of the STEEP Framework, it emerges that the necessary and sufficient conditions for deploying hydrogen homes are substantially more dynamic and diverge across segments of the population. Notably, positive emotions is not a prerequisite for social acceptance but may be required to facilitate high levels of perceived adoption potential. However, even if adoption potential were to be maximised, this would not necessarily translate to high levels of adoption intention and subsequent installation for hydrogen heating and cooking technologies. In illuminating this reality, Fig. 1 draws attention to the potential intention-behaviour gap underlying mechanisms of acceptance and adoption within the innovation-decision making process [217,359].

As the transition unfolds, among other constructs, the role of financial perceptions is likely to change as perceived affordability takes on increasing importance [360]. The literature supports the notion that consumers place more weight on financial factors as the adoption decision draws nearer, as opposed to being distant and hypothetical [44, 137,238]. At this juncture, while navigating hypothetical market choices involving several heterogeneous variables, consumers are more likely to fixate on salient factors such as technology performance as opposed to unknowns such as energy consumption costs [361]. In the future, it may be the case that positive financial perceptions are a prerequisite for enabling adoption prospects for hydrogen homes.

Cross-sectional insights captured in this study should be supported by a comprehensive, longitudinal evidence base to derive more emphatic conclusions, especially regarding how the perceptual and emotional (as well as cognitive) antecedents of adoption potential and intention may shift as the hydrogen sector matures. Cross-national research is a fruitful area for attesting to the generalisability of recent findings from Australia and Europe, in addition to the UK context as captured between October and December 2022.

Finally, while this analysis focused exclusively on consumer perceptions, understanding the perspectives of other actors is critical for supporting strategic policy making and managerial decisions [362]. Critically, the role of intermediary actors such as industry associations [363] and non-government organisations [364], as well as middle actors such as building professionals [365,366], will further shape the dynamics for deploying hydrogen homes at a meaningful scale [44,253]. The next logical step is to position the consumer-oriented perspective presented via the STEEP Framework within the broader context of multi-actor processes underlying the contested transition to hydrogen homes. Realising this research agenda would mark a definitive turning point in identifying and demarcating the necessary and sufficient conditions for deploying hydrogen homes.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Joel Adam Gordon reports financial support was provided by the UK Research and Innovation Engineering and Physical Sciences Research Council. Joel Adam Gordon reports financial support was provided by Cadent Gas Ltd. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nazmiye Balta-Ozkan:** Conceptualization, Writing – original draft, Funding acquisition, Project administration, Supervision. **Anwar Haq:** Conceptualization, Writing – original draft. **Sayed Ali Nabavi:** Funding acquisition, Project administration, Supervision.

Data availability

Data will be accessible publicly on our institutional data repository. <https://doi.org/10.17862/cranfield.rd.25730196.v1>.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2024.04.352>.

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2024-06-05

Elsevier

<https://doi.org/10.1016/j.ijhydene.2024.04.352>

Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. (2024) Necessary and sufficient conditions for deploying hydrogen homes: a consumer-oriented perspective. International Journal of Hydrogen Energy, Volume 69, June 2024, pp. 982-1021