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Heterogeneous preferences for living in a hydrogen home: an advanced multigroup analysis†

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The UK Hydrogen Strategy (August 2021) and subsequent Heat and Buildings Strategy (October 2021) affirm that a strategic decision is set to be taken by 2026 on the prospect of residential decarbonisation *via* 'hydrogen homes'. As this decision date draws nearer, quantitative insights on consumer perceptions of hydrogen-fuelled heating and cooking appliances remain limited. The existing knowledge deficit presents a substantial barrier to implementing a socially acceptable deployment pathway for residential decarbonisation. Despite recent efforts to advance the social science research agenda on hydrogen acceptance, few studies have advanced theoretical knowledge or pursued comprehensive statistical analyses. This study responds to the extant research gap by analysing the perceived adoption potential for hydrogen homes *via* partial least squares-necessary condition-multigroup analysis. Drawing on data from a nationally representative online survey ($N = 1845$) conducted in the UK, the adoption dynamics for domestic hydrogen are compared across four sub-groups of the population. The findings suggest that non-economic constructs such as safety perceptions and production perceptions are potentially more influential at this stage of the domestic hydrogen transition. Differences between consumer sub-groups are explained by safety, technology, and production perceptions, whereas financial perceptions are relatively homogeneous across the segments. These patterns underline the opportunity to strengthen residential decarbonisation efforts through segment-specific polices and strategic engagement with different parts of the housing stock. Policy makers and key stakeholders should factor consumer heterogeneity into net-zero decision-making processes by firstly acknowledging the amplifying effect of technology and environmental engagement in supporting adoption prospects for hydrogen homes. Socially acceptable strategies for decarbonising the residential sector can be supported by actively responding to heterogeneous household preferences for living in a hydrogen home.

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1 Introduction

Accelerating residential decarbonisation is critical to realising a net-zero energy future in the United Kingdom (UK)[1,2] and many countries around the world;[3,4] several of which share an oceanic climate, dependency on fossil fuels for heating, and targets for reducing greenhouse gas (GHG) emissions.[5] Currently, around 38% of the UK's natural gas demand is used for residential heating,[6] which accounts for approximately 14% of national GHG emissions.[7] However, for several years, the residential sector has remained at the margins of system-wide decarbonisation efforts;[8] following a primary focus on phasing out coal power[9] and scaling up renewables to reduce emissions from the electricity sector.[10]

Consequently, targets for decarbonising the housing stock have fallen short;[11] owing in part to prolonged consumer resistance towards low-carbon alternatives such as heat pumps[12,13] and inconsistent government strategies.[2,14,15] For example, in their recent systematic review of developments in national heat pump markets, Gaur *et al.*[13] identified a range of regulatory, economic, structural, and infrastructure barriers, in addition to issues of social acceptance. In the UK context, Lamb and Elmes[16] recently estimated the technical and market readiness of UK households for adopting heat pumps to be 34.7% and 11.1%, respectively, while awareness of sustainable heating technologies remains low.[17]

In its Sixth Budget Report released in 2020, the Committee on Climate Change (CCC) recommended a predominantly electrified pathway for heat decarbonisation, wherein 11% of homes in proximity to industrial clusters could potentially switch to hydrogen. Following the UK Hydrogen Strategy (August 2021)[18] and subsequent Heat and Buildings Strategy (October 2021),[19] the prospective technology portfolio[20,21] includes hydrogen-fuelled appliances for domestic space heating, hot water, and cooking.[22–24] Under an optimistic scenario, the government recognised a potential for converting up to four million households (~16.6% of the housing stock) to domestic

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hydrogen by 2035;[25] should the use case be established following a series of demonstration projects[26,27] and local trials.[28–30] However, in October 2023, the National Infrastructure Committee (NIC)[31] rejected the premise that residential hydrogen heating should be included in the UK policy mix.

The NIC based their modelling assumptions for the period 2025–2050 on a scenario where domestic hydrogen is sourced predominantly from electrolysis of water using low-carbon electricity.[31] Under this assumption, electricity for making green hydrogen accounts for 90% of the production cost, which constrains the economic case for hydrogen in domestic heating.‡[32,33] While a 'green' hydrogen pathway could see total system cost ranging 1410 to 1800 £ per year, this figure deceases to 1150 £ per year when hydrogen is produced *via* a 'blue' pathway (*i.e.* steam methane reformation with carbon capture and storage).[34] However, electric heat pumps remain more price-competitive (790–880 £ per year under different scenarios). Nevertheless, a recent meta-review of 54 studies on hydrogen heating[35] focuses on the least price-competitive hydrogen pathway, while offering minimal reflection on scenarios where hydrogen may diffuse beyond a niche scale,[36] as further discussed in ESI Note 1 (see ESI1†).

While influential evidence could emerge within the next years, the UK government has since clarified that electrification of residential heating *via* heat pumps, and to a lesser extent heat networks, will be the primary technology pathway in the short-term and for reaching net zero.[37] At present, the government maintains its conviction that more extensive analysis should be conducted before a policy decision is taken in 2026.[37] Accordingly, the Department of Energy Security and Net Zero (DESNZ) continues to appraise evidence on the safety, feasibility, and acceptability of domestic hydrogen.[37]

Social acceptance will play a significant role in shaping decarbonisation pathways for the residential sector,[38,39] with the government stating that the transition should be consumer led and delivered in sync with the natural replacement cycles of household heating systems.[37] However, the DESNZ is yet to establish an overarching long-term consumer engagement plan to support the decarbonisation of home heating, and by proxy, cooking.[37]

While this study focuses on the UK context, it is currently anticipated that hydrogen will play a relatively limited role in global residential decarbonisation.[35] However, one limitation of available studies[35] (see ESI1†) is that techno-economic assessments lack behavioural realism,[36] since consumer heterogeneity is more challenging to model and typically represented in a stylised fashion through simplified economic relationships.[40] Relatedly, accounting for heterogeneity is fundamental to improving "precision in the identification and evaluation of causal mechanisms,"[41] which motivates the use of structural equation modelling (SEM). However, ahead of a potentially 'critical juncture'[42] in the UK's energy future,[43,44] – which could shape the feasibility of developing a national hydrogen economy[45] – researchers are yet to examine the role of consumer heterogeneity[41,46,47] in shaping potential market acceptance for 'hydrogen homes'.[38,48]

To date, research on domestic hydrogen has applied a techno-economic perspective,[7,34,49] employing tools such as the UK Times Model to examine technology pathways for heat decarbonisation.§[44,50] Although primarily concentrated on aspects such as network investments, fuel types, costs, and emissions,[50] forecasters also recognise that factors such as demographics, social habits, public views towards heating, and underlying levels of acceptability will influence domestic energy demand and market developments.[5,21]

Initial efforts have been taken to advance the social science research agenda on domestic hydrogen,[39] as reflected by a recent uptake of largely qualitative studies.[23,43,51,52] However, as emphasised by Almaraz *et al.*,[53] advanced statistical analysis is needed to increase the robustness of quantitative evidence on public perceptions of the hydrogen economy.[54] Moreover, a more realistic and strategic understanding of market acceptance dynamics can be supported by internalising consumer heterogeneity into decision-making:[40,55,56]

"When studied systematically, heterogeneity can be leveraged to build more complete theories of causal mechanism that could inform nuanced and dependable guidance to policymakers."[57]

In response, this study aims to advance the empirical evidence base on consumer attitudes towards the domestic hydrogen transition in the UK context by employing multigroup analysis (MGA). As outlined in Section 2.1, the sample is composed of four consumer segments, which are distinguished according to their level of technology and environmental engagement, and socio-economic status.

To overcome the limitations of prior research efforts[39,58,59] and minimise the risk of invalid recommendations,[60,61] this study employs partial least squares multigroup analysis (PLS-MGA) and multigroup necessary condition analysis (MG-NCA). As described in Section 2 and reported in Section 6, PLS-MGA evaluates the determinants of perceived adoption potential from a sufficiency perspective,[62–64] while MG-NCA examines the influence of critical success factors from a necessity perspective.[65–67] While hydrogen heating is the focal point of policy and research interest,[35] this study provides an important continuum to prior research by accounting for the potential role of hydrogen cooking in future transition pathways.[52,68]

Following this introduction, Section 2 reports the research design and methodology, while Section 3 reviews the literature on MGA. Subsequently, Section 4 develops a series of testable hypotheses to support the partial least squares-necessary condition-multigroup analysis (PLS-NC-MGA) approach. Section 5 formalises the conceptual framework for examining consumer heterogeneity in the context of perceived adoption

‡ The NIC calculated a negative cost difference of £115 per household when hydrogen heating is supplied to 38% of the housing stock (46% use heat pumps) as opposed to 13% of properties (71% use heat pumps). A scenario without domestic hydrogen playing a niche role (83% heat pump penetration by 2050) suggested a saving of £270 per household.

§ For example, Calvillo *et al.*[50] modelled a scenario wherein hydrogen is used in just over 5% of UK households by 2035, before growing to 42% by 2040 and reaching 56.6% by 2050.

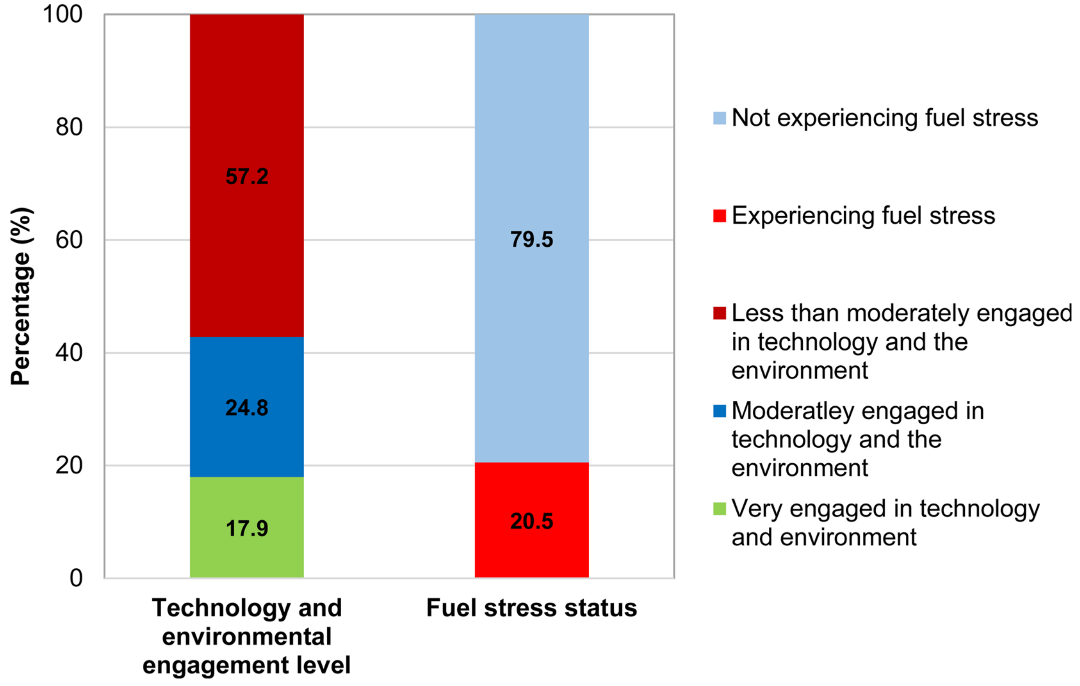

Fig. 1 Composition of consumer sub-groups by categorical filters. Light blue bar (79.5%) = cumulative percentage of the BLG (36.8%), MEG (24.8%), and VEG (17.9%); dark red bar (57.2%) = cumulative percentage of the BLG (37.6%) and FSG (20.5%).

potential for hydrogen homes. Section 6 reports the statistical results following the application of advanced MGA, while Section 7 discusses the implications of the findings and identifies potential sources of consumer heterogeneity. Finally, Section 8 concludes the study by outlining opportunities for advancing the social science research agenda on hydrogen homes.[39]

2 Materials and methods

Research practitioners should follow up-to-date guidelines and adhere to best practices when employing PLS-SEM[69,70] and implementing PLS-MGA,[64,71] alongside (multigroup) necessary condition analysis (NCA).[67,72,73] These complementary methods were employed systematically throughout this analysis,[64,74] as described in the following subs-sections. Firstly, Section 2.1 outlines the research design and sampling approach, before reporting the procedures for PLS-MGA in Section 2.3 and MG-NCA in Section 2.4. Overall, the advanced methodology employed in this study reflects recent research efforts to combine a suite of PLS-SEM tools and complementary statistical approaches.[72,75–77]

2.1 Research design and sampling approach

This study examines data collected through an online survey which closed on December 23rd, 2022. The survey aimed to collect information on consumer attitudes towards the domestic hydrogen transition in the UK context. The survey instruments were fine-tuned through literature review findings[38,48,78,79] and qualitative results from online focus groups,[43,52,80] and further validated through pilot tests and inputs from academics (social scientists and hydrogen experts). Qualtrics software[81] was employed to program the survey, with content and face validity established ahead of final deployment in October 2022. Full details of the survey questions, answers scales, and references to supporting literature are provided in ESI2.†

A broadly nationally representative sample ($N = 1845$) was secured by implementing quotas for socio-structural variables (*i.e.* housing tenure, property type) and socio-demographic characteristics[82] (*i.e.* age, gender, income), in addition to a quota for location (see ESI2†). Notably, recent research underscores the place-specific dynamics of the UK domestic hydrogen transition, which sees deployment of hydrogen homes primarily targeted for the north of England in proximity to industrial towns.[38] The potential influence of respective socio-structural and socio-demographic variables[82] are explored in Section 6.6.

This study advances the literature by exploring the extent to which concern for climate change and associated environmental issues, engagement in renewable energy technology, and conditions of fuel stress may influence domestic hydrogen adoption potential. As described in Section 3.2, heterogeneous consumer preferences can shape prospects for technology adoption and impact the feasibility of low-carbon energy transitions. Four distinct sub-groups were targeted (see Fig. 1 and 2): a Moderately technology and environmentally Engaged Group (MEG); a Very technology and environmentally Engaged Group (VEG); a Fuel Stressed Group (FSG) with less than moderate levels of technology and environmental engagement; and a Baseline Group (BLG) which filtered out all previous categories (see Table 1).¶ The inclusion of a fuel stressed group

¶ As a result, the sampling approach increases national representativeness by combining a control group (*i.e.* the BLG) with three specific sub-groups.

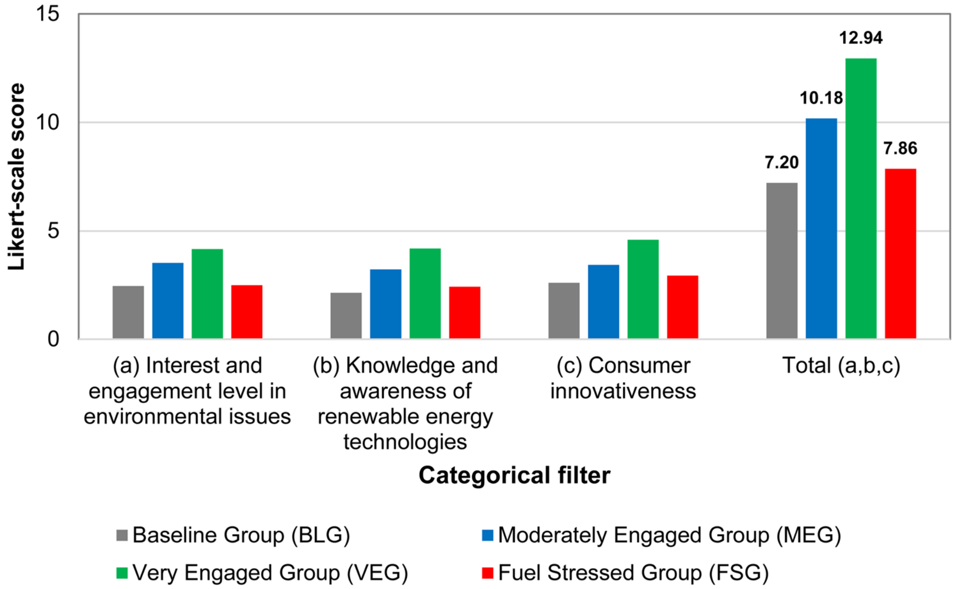

Fig. 2 Responses to filtering questions across consumer sub-groups.

Table 1 Consumer sub-groups composing the survey sample

Sub-group	Consumer specifications
Moderately engaged group (MEG) $N = 458$	• Moderate level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Moderate interest and engagement in environmental issues • Not experiencing fuel stress
Very engaged group (VEG) $N = 331$	• High level of knowledge and awareness of renewable energy technologies • At least moderate level of interest in adopting new energy technologies • Strong interest and engagement in environmental issues • Not experiencing fuel stress
Fuel stressed group (FSG) $N = 379$	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Living in fuel poverty or experiencing high levels of fuel stress
Baseline group (BLG) $N = 677$	• Less than moderate level of knowledge and awareness of renewable energy technologies • Less than moderate level of interest in adopting new energy technologies • Less than moderate level of interest and engagement in environmental issues • Not experiencing fuel stress

is particularly important for counteracting the risks inherent within a 'heterogeneity-naïve paradigm', whereby vulnerable or marginalised groups may be overlooked prior to policy recommendations.[57]

Accordingly, this study contends that differences in technology and engagement levels, and socio-economic conditions, will influence consumer attitudes towards the domestic hydrogen transition.[38,48,83] The decision to introduce segmentation *via* technology and environmental engagement filters, in addition to fuel stress (see ESI3†) provides an important continuum to recent research carried out in the UK,[43,52,80] while significantly advancing prior engagement with the topic of hydrogen acceptance.[58,84,85] Specifically, Gordon *et al.*[43,52,80] laid the foundations for this study by conducting ten online focus groups ($N = 58$), which compared a range of consumer segments, defined according to five categories: interest in renewable energy and joining a renewable energy community; ownership of solar PV panels and multiple smart home technologies; active engagement in environmental issues; facing fuel poverty or high levels of fuel stress; and living in an industrial city or town.

Following the research design, sample size requirements[86] are evaluated at the sub-group level[71] using statistical power tests,[87,88] as illustrated in ESI4.† With six predictor variables, one mediating variable, and one dependent variable, the smallest sub-sample in this study ($N = 331$) is sufficient to detect a moderate effect size ($f^2 = 0.065$) at a 95% significance level ($\rho < 0.05$). Furthermore, the largest sub-sample can detect a smaller effect size ($f^2 = 0.035$), as indicated by G-Power software analysis.[89,90]

To rule out the risk of common method bias (CMB)[91] in survey responses,[92] Harman's single factor test was applied,[93] which returned an overall variance significantly below the acceptable threshold of 50% (see ESI5†). Additionally, following the method of Kock *et al.*[94] a random variable was generated to serve as the sole endogenous construct within each model, which returned variance inflation factor (VIF) scores below the threshold of 3.0 for each model.[91] Finally, no instances of skewness or kurtosis were present among the measurement items[88,95] since all values were between −2 and +2 (see ESI6†), suggesting the symmetry and distribution of the sample is appropriate for analysis in PLS-SEM.[88,96]

2.2 One-way analysis of variance

Prior to conducting PLS-MGA, descriptive statistics are firstly analysed using IBM SPSS Statistics 28.0 (ref. 97) to demarcate the perceived adoption potential of each sub-group. Additionally, a series of Kruskal–Wallis (K–W) non-parametric H-tests[98] are undertaken to compare adoption potential between consumer segments. This procedure supports the preliminary analysis ahead of more rigorous statistical analysis *via* PLS-MGA (see Section 6.4) and MG-NCA (see Section 6.6). Specifically, the K–W test provides an adaptation of classical one-way analysis of variance (ANOVA)[99,100] to compare the median ranks of more than two independent groups,[101,102] wherein the null hypothesis (H_0) states that the median ranks of each group are the same.[103] However, the K–W test is not without its limitations (see ESI7).

2.3 Partial least squares multigroup analysis

PLS-SEM is a well-stablished research method[104,105] for measuring and analysing the relationship between observed and latent variables.[106–108] PLS-SEM is based on ordinary least squares regression, which calculates both the variance and covariances of variables to estimate regression coefficients.[109] Researchers employ the approach to test hypotheses within a conceptually-grounded path model.[110]

Critically, PLS-SEM is the recommended approach when theoretical development is required and the focus is on exploration and prediction,[63,111,112] as opposed to theory confirmation.‖[113,114] As a result, the technique has gained increasing traction among social scientists for advancing exploratory research[95,113] across a wide range of domains,[64,104] such as smart energy technology adoption[115–117] and hydrogen acceptance.[118–120] In view of the need to advance theoretical understanding and empirical evidence[47,78] on domestic hydrogen adoption potential,[23,51] this study undertakes PLS-MGA using SmartPLS 4.1 software.[121]

Since "customers from different market segments can have very different belief structures,"[122] social scientists often measure "latent variables (*e.g.* personality traits, attitudes) for several groups in order to evaluate between-group differences therein."[123] As articulated by Becker *et al.*,[61] it is often unrealistic to assume that survey data in social science research can be treated as a homogenous sample representing a single population. For example, pooling data for two categories such as gender would imply a homogenous population (*i.e.* male and female respondents), thus path coefficient estimates could fail to account for the underlying heterogeneity within the sample.[74] Similarly, researchers may explore other socio-demographic variables such as age. Notably, Poortinga *et al.*[124],** recently examined generational differences in relation to climate change engagement among the five named generation groups.††

Understanding the rationale of MGA stems from recognising the role of moderators, which Frazier *et al.*[125] characterise as "addressing 'when' or 'for whom' a variable most strongly predicts an outcome variable." Thus, moderating variables are critical for assessing whether two variables share the same relation across groups.[126,127] In situations where the moderator is categorical (*e.g.* nationalities, gender *etc.*) and the goal is to test the moderation effect on the entire model (*i.e.* all structural paths), the recommended analytical technique is MGA.[74,126]

PLS-MGA is an established method for efficiently testing moderation across multiple relationships in a structural model,[64,128] thereby accounting for the presence of group-specific differences.[129] The method tests the null hypothesis that the population parameters (*i.e.* structural path coefficients) are equal across two sub-groups (H_0: $\theta^{(1)} = \theta^{(2)}$).[128] Thus, PLS-MGA functions by testing whether statistically significant differences exist between sub-groups, which the researcher identifies *a priori* during the sampling stage (*i.e.* BLG, MEG, VEG, FSG),‡‡ as further discussed in ESI Note 8 (see ESI9†).

PLS-MGA is conducted in six stages to examine whether the perceptions and behavioural intentions of different consumer sub-groups are heterogeneous in respect to domestic hydrogen appliances (see Fig. 3). The first stage involves defining how the groups are generated and specifying sample size requirements§§ for achieving statistical power, as outlined in Section 2.1. The second stage involves validating the measurement model through requisite checks for reliability and validity. Subsequently, the measurement invariance test of composite models (MICOM) procedure[130] is employed to determine whether group comparisons are feasible.[131]

The first step of the MICOM procedure involves establishing configural invariance, whereby the constructs are equally parameterised and estimated between each sub-group.[130] Secondly, compositional invariance must be achieved by verifying that the "original correlation" is equal to or greater than the 5%, or by ensuring the *p*-value is non-significant. When both configural

‖ When models and hypotheses have been thoroughly developed, covariance based structural equation modelling (CB-SEM) can be applied for theory testing and confirmation.[70] The differences between CB-SEM and PLS-SEM are extensively documented in the literature and remain contested.[109,113]

** The study applied first-generation regression techniques as opposed to structural equation modelling.

†† *i.e.* Generation Z, Millennials, Generation X, Boomers II, Boomers I and older.

‡‡ This approach is distinct from a posterior approach wherein the research tests for unobserved heterogeneity within the data to identify the plausibility of different segments or 'clusters'.[60,61]

§§ Nevertheless, many researchers fail to meet sample size requirements, such as the study of Murbarak and Petraite[132] which compared Malaysia ($N = 124$), Indonesia ($N = 109$), and Thailand ($N = 91$).

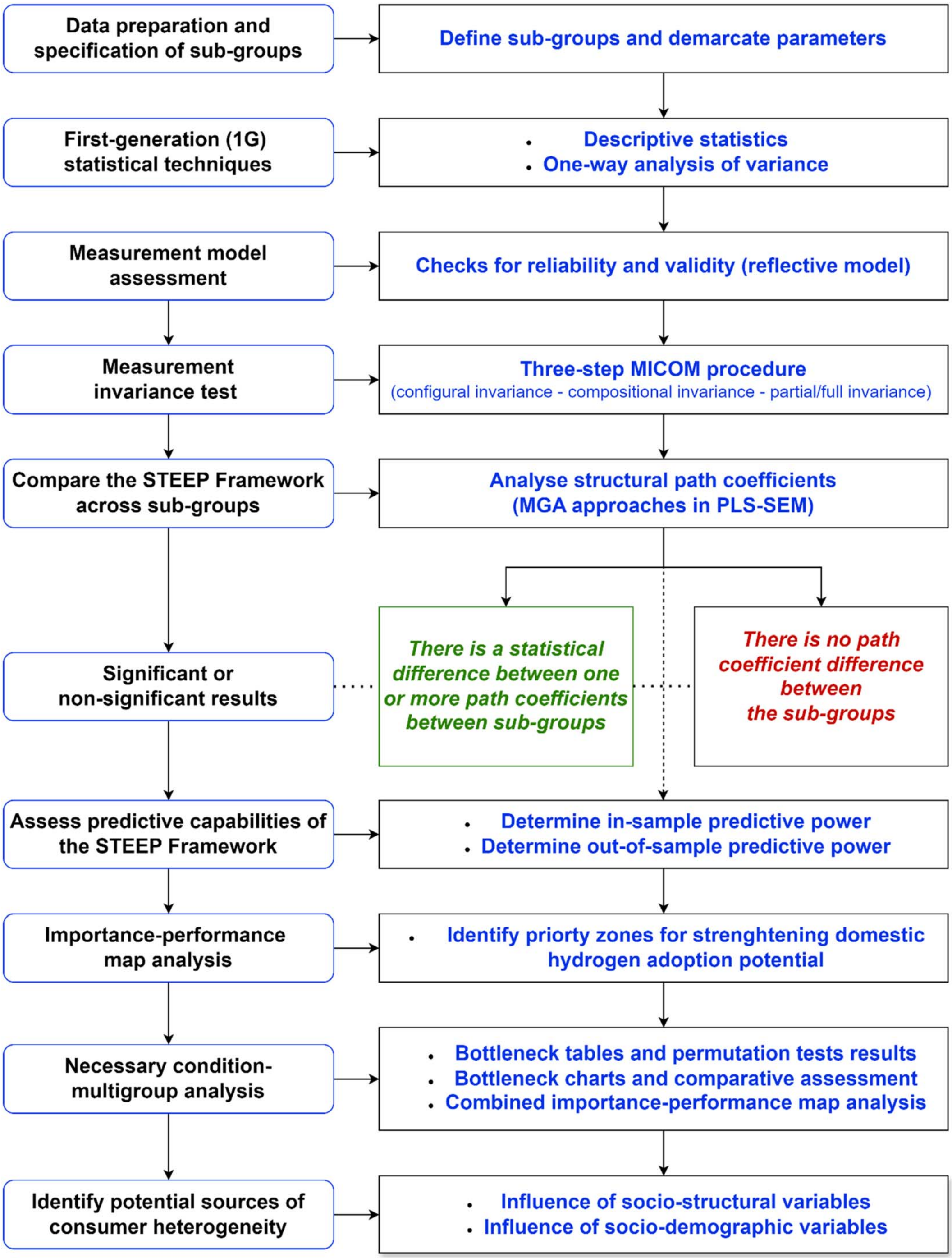

Fig. 3 Research procedure for performing PLS-NC-MGA. Source: Authors' design based on ref. 64, 65, 72–74 and 130.

and compositional invariance are established, full measurement invariance (*i.e.* composite equality) is plausible, provided both the mean and variance of the "original differences" fall between the lower (2.5%) and upper boundaries (97.5%). Alternatively, partial invariance is established when none or just one of the mean values or original differences falls between the lower and upper boundaries.[64,74,130]

Following the MICOM procedure – which satisfied the conditions for establishing at least partial measurement invariance (see Section 6.3) – the differences between path coefficients for respective pairwise comparisons are analysed using available parametric and non-parametric tests[64] in SmartPLS 4.1.[121] In cases where statistically significant group-specific differences are observed,[130] the next step involves analysing the structural model for each sub-group, including an assessment of in-sample and out-of-sample predictive power.

Subsequently, the modelling results are compared *via* an importance-performance map analysis (IMPA)[132,133] to identify areas of strategic importance for supporting consumer acceptance. IMPA is leveraged to examine the critical success and resistance factors shaping perceived adoption potential for hydrogen homes, while combined importance-performance map analysis (cIMPA) is applied to deepen insights on identified success factors within the STEEP Framework (*i.e.* safety perceptions, technology perceptions, and production perceptions). In the final stage, the statistical findings are further explored by examining potential sources of consumer heterogeneity linked to socio-structural and socio-demographic variables.

2.4 Multigroup necessary condition analysis

As an emerging research method, necessary condition analysis (NCA)[65] provides researchers with a data analysis technique for identifying the 'must-have' factors for enabling a target outcome such as domestic hydrogen adoption.[68] A necessary condition implies that a specific factor cannot be compensated for by the presence of other factors.[65] Moreover, NCA quantifies the level of a critical success factor that is needed to produce the desired objective,[65,134] which is relayed *via* 'bottleneck tables' (*i.e.* a tabular representation each ceiling line wherein each row corresponds to a specific outcome level).[65,135]

When implementing NCA, ceiling lines are demarcated within in an XY scatter plot to establish the area with and without data points, which informs the scope of observing an empty space in the upper left area.[65,136] The ceiling envelopment free disposal hull (CE-FDH) is the default non-parametric option; generating a non-decreasing step function ceiling line (*i.e.* a piecewise linear function along the upper left observations), which should be employed in situations of significant deviation between alternative ceiling line results (see ESI8†).[65] Detecting an empty space *via* the CE-FDH implies that predictor X (*i.e.* safety perceptions) constrains outcome Y (*i.e.* perceived adoption potential), with a larger space corresponding to a more significant constraint.

Dul[136] developed a statistical significance test, which suggests the following cut-offs as guidelines: a necessity effect size (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. For each case, the permutation p-value must also be significant at the 95% level ($p < 0.05$) to support the presence of a necessary condition.

While Dul and colleagues have established NCA and guidelines for its application[66] across a wide range of research areas,[137–141] including environmental and social impact assessment[142] and the renewable energy transition,[143] the combined use of PLS-SEM and NCA is a more recent research advancement.[73] Richter *et al.*[67,73] pioneered this integration to support theory development through "complementary views of causality and data analysis," which has been demonstrated across a range of contexts including studies on the transport sector,[77,144,145] consumer behaviour,[75] and sustainable business.[146] Through the combined use of PLS-SEM and NCA, researchers can leverage insights from both a sufficiency and necessity perspective to communicate actionable insights to decision-makers,[73] which can be enhanced through the use of combined importance-performance map analysis (cIMPA).[72]

cIMPA pools data from PLS-SEM and NCA to extend findings from a traditional IMPA through the inclusion of bottleneck sizes within the matrix.[72] Within IMPA, importance is plotted on the x-axis to show total effects for predictors composing the structural model, while average performance is plotted on the y-axis to capture the average rescaled latent variable scores (0–100). The novelty comes from integrating bottleneck percentages from NCA into the output, which enriches empirical insights by displaying the level to which a given factor has failed to be achieved, as illustrated by Hauff *et al.*[72] when testing an adapted version of the technology acceptance model (TAM).[147]

This study applies these emerging methods to advance the use of multigroup necessary condition analysis (MG-NCA), which is supported through the addition of 'bottleneck charts', as an accessible approach for visualising results from bottleneck tables for multiple sub-groups.

2.5 Summary of methods

In its totality, this study advances the use of partial least squares-necessary condition-multigroup analysis (PLS-NC-MGA), which constitutes an incremental methodological contribution to the literature.[148] Fig. 3 demonstrates the multi-stage research method, which adheres to the following sequence within the paper: reporting results from descriptive statistics and one-way analysis of variance (ANOVA) tests in Section 6.1; carrying out the measurement model assessment for each sub-group in Section 6.2; conducting the measurement invariance test of composite models (MICOM) procedure in Section 6.3; evaluating the structural model in for each sub-group and analysing the difference between path coefficients *via* PLS-MGA in Section 6.4; extending the assessment *via* IMPA in Section 6.5; implementing MG-NCA in Section 6.6; and identifying potential sources of consumer heterogeneity in the Discussion section (7) to crystallise the analysis.

3 Literature review

To date, the scientific literature has focused primarily on techno-economic assessments of hydrogen production pathways,[149,150] alongside models and forecasts for the hydrogen economy.[44,151–153] In parallel, researchers have examined the technological innovation system for hydrogen fuel cells,[154–156] with recent studies also focusing on maritime applications,[157] the steel industry,[158] alongside the broader hydrogen economy.[159,160] Furthermore, a new evidence base is emerging on stakeholder perspectives of the hydrogen industry, which can help support strategic policy interventions.[161–165] Consumer studies have centred mostly on hydrogen fuel cell vehicles (HFCVs),[166] including a focus on early adoption dynamics[167] and motivational drivers.[168] Nevertheless, recent theoretical[38,78] and empirical contributions on domestic hydrogen acceptance[47,120] have also advanced the literature.[39,53,169] Against this background, the following sub-sections provide a contextual review to support MGA.

3.1 Scopus search results on PLS-SEM and PLS-MGA

An entry point into this analysis is the recent review article of Cheah *et al.*[64] in the *J. Bus. Res.* The authors conducted a keyword search (article title, abstract, and keywords) on "PLS-SEM Multigroup Analysis"¶¶ in Science Direct and Scopus for the period 2010–2021, which returned 378 articles sourced from 183 journals.[64] The search results included 350 articles since 2017, with the highest frequency within the final year ($N = 118$). The principle finding of the search was to highlight the paucity of studies which analysed more than two groups.[64] Specifically, since 2017, one in five studies applied PLS-MGA to more than two groups.‖‖

In view of findings of Cheah and colleagues,[64] a Scopus search (article title, abstract, and keywords) for "PLS-SEM" AND "energy" was conducted, which returned 188 journal articles for the period 2017–2023. The results show a recent proliferation of PLS-SEM in energy studies, reflected by a five-fold increase since 2020. A subsequent search in Scopus targeted the following keywords in article title, abstract, and keywords: "PLS-SEM" AND "multigroup" OR "multi-group" AND "technology." The search returned 66 journal articles with sustained growth since 2021. Notably, filtering the results by subject area in Scopus reflects a scarcity of PLS-MGA studies among energy researchers ($N = 5$),*** whereas the fields of business, management, and accounting ($N = 33$), social sciences ($N = 30$), and computer science ($N = 18$) dominate the sample.†††

The growth dynamics of PLS-SEM among energy researchers and the modest uptake of PLS-MGA in technology acceptance studies is captured in Fig. 4. Foremost, the initial exploration corroborates the comparative paucity of multigroup analyses within the PLS-SEM field,[64] which mirror the wider literature in typically focusing on comparisons between gender,[170,171] age,[56,124,172] income,[173–175] or country.[176,177] Nevertheless, some researchers such as Kaur *et al.*[178] have responded by accounting for multiple variables such as gender, income, occupation type, and education level when examining the green buying intentions of millennials in India. The study reported significant differences regarding the influence of monthly income and education level.[178] The importance of socio-demographic variables has also been emphasised by Girod *et al.*[179] noting that willingness to adopt smart thermostats in Germany registered highest among young men with high savings potential (*i.e.* low apartment occupancy and high energy use) and a high income and education level.

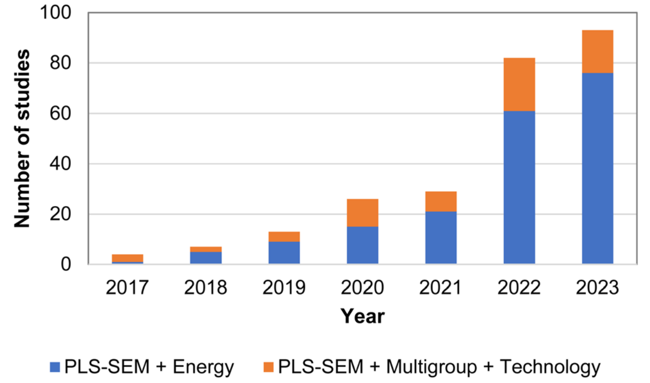

Fig. 4 Comparison between Scopus search results for PLS-SEM and PLS-MGA.

To supplement and further validate insights related to MGA, an additional key word search was implemented in Scopus (article title, abstract, and keywords) for "multigroup analysis OR multi-group analysis" AND "structural equation modelling" OR "structural equation modelling" OR "SEM" OR "PLS-SEM," which returned 1380 articles for the period 2012 to 2023 (see Fig. 5).‡‡‡ As displayed in Fig. 6, energy studies represent a small fraction of the sample (~3.2%), while MGA features somewhat more prominently in the environmental sciences (~6.1%), which is consistent with the results supporting Fig. 4.

Following the Scopus search, ESI Note 9† provides a summary of ten impactful studies which applied MGA across a range of areas, such as e-commerce,[172,180,181] e-learning,[182] and eco-purchasing, wherein Barbarossa and De Pelsmacker[55] compared green consumers ($N = 453$) and non-green consumers ($N = 473$) in the Italian context.[55] Seminal contributions to the literature further reflect a constraint of two-group comparisons or a narrow focus on socio-demographic moderators such as gender and age, as reflected within the UTAUT.[183]

Among numerous examples, scholars have leveraged MGA to examine eco-friendly purchasing behaviour,[177] intentions to purchase organic food,[177] the antecedents of corporate social responsibility,[184] and the role of agricultural education in the circular economy.[185] Additionally, researchers have employed MGA to investigate energy behaviours among rural residents,[186] behavioural intention to ride in autonomous vehicles,[187] adoption intention of battery electric vehicles,[188] purchase intention for hydrogen automobiles,[175] and purchase intention towards energy efficient appliances.[189]

Environmental policy makers also seek information on different segments of the population to support more equitable decision-making.[190] Meanwhile, within a specific sub-group such as nonindustrial private forest owners in the United States, research shows that individuals are unlikely to respond similarly to forest policies intended "to motivate certain

¶¶ Including the following derivatives: "PLS-SEM Multigroup", "PLS-MGA", and PLS Multigroup".

‖‖ 2017 = 16.7%; 2018 = 21.6%; 2019 = 19.3%; 2020 = 18.2%; 2021 = 24.2%. Standard deviation for the period = 2.97.

*** Seven studies corresponded to the field of environmental science.

††† Notably, in their review of articles with PLS-SEM applications in Industrial Marketing Management Journal, Guenther *et al.*[334] retrieved 139 articles for the period 1998–2020, which mirrors the Scopus search results. Magno *et al.*[412] also retrieved 177 articles from eight quality management journals for 2003–2021, which reflected a doubling in outputs between 2020 ($N = 15$) and 2021 ($N = 30$).

‡‡‡ 2012 and 2013 marked the first consecutive years where results exceeded 20 articles.

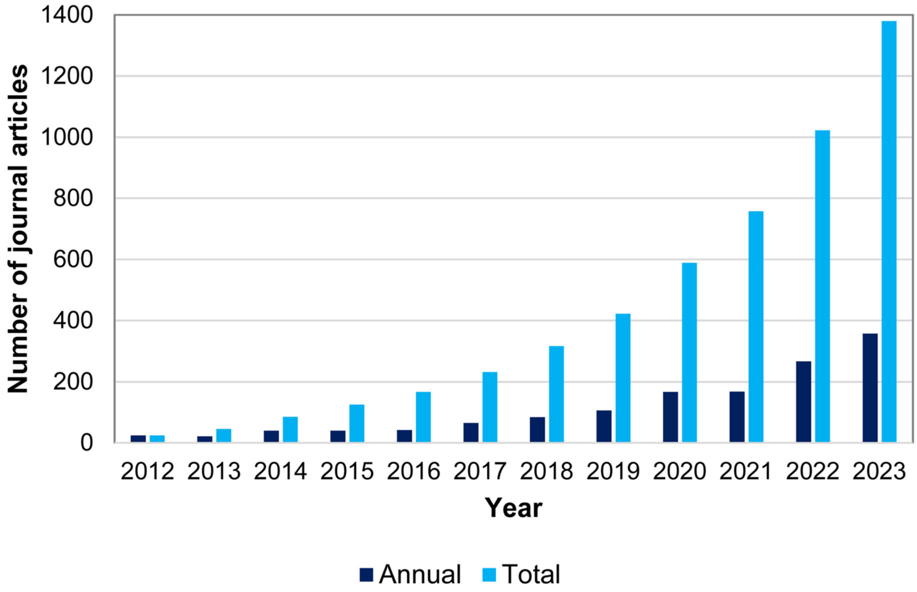

Fig. 5 Scopus search results for articles employing SEM-based multigroup analysis.

investment, managements, and harvest behaviour." Additionally, research conducted in Belgium provides strong evidence that consumer innovativeness and environmental concern significantly influence intention to adopt an electric car.[191] Against this background, the next sub-section undertakes a more targeted review of multigroup analyses within the field of energy technology acceptance, as a means for developing a series of testable hypotheses.

3.2 International studies with a focus on consumer heterogeneity

Social scientists have increasingly recognised the important role of consumer heterogeneity in shaping technology diffusion and policy making (see ESI10 and ESI11†). However, systematic analyses of consumer heterogeneity remain relatively scarce in the energy technology acceptance literature.[192] To an extent, the deficiency of a multigroup focus (especially extending beyond

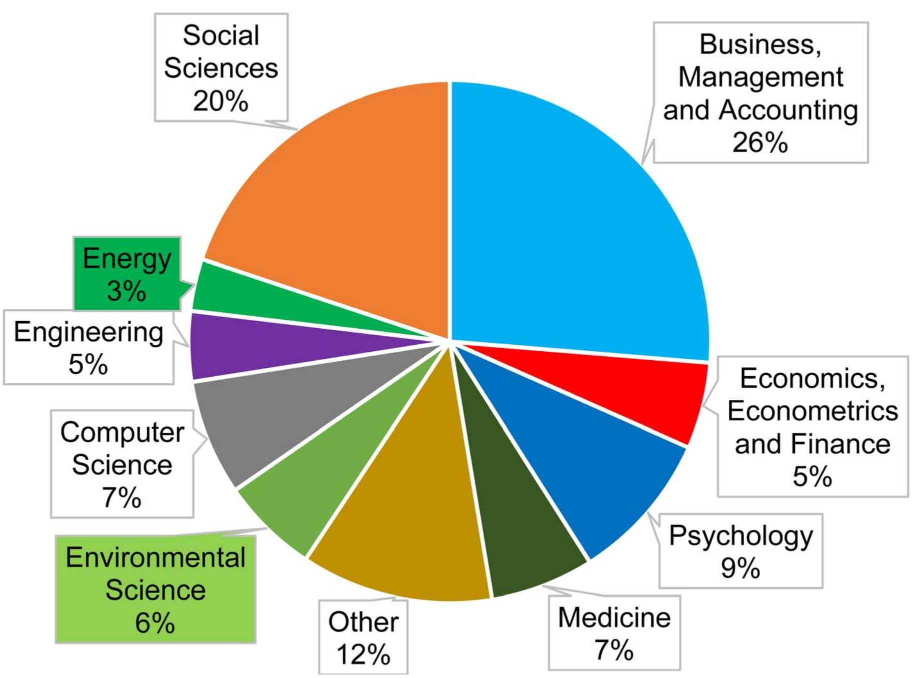

Fig. 6 Prevalence of studies using SEM-based multigroup analysis by research field.

two dimensions), reflects a persistent trend towards implementing ineffective, one-size-fits-all energy policies in different country contexts, such as China,[192] South Africa,[193] Austria,[194] Denmark,[195] the US,[196] and the UK.[197]

Notably, Roddis *et al.*[198] demonstrate the extent to which support for energy sources may vary across different regions of the UK, as outlined in ESI Note 11 (see ESI11†), further motivating the need for segmentation-specific analyses.[199,200] The need to mitigate the risk of one-size-fits-all approaches has also been emphasised in the field of medical research, where researchers are increasingly employing analytical algorithms to understand heterogeneity among patients.[201] Similarly, the three-year longitudinal study conducted by Jurison[202],§§§ reached the following conclusion: "…differentiated implementation strategies focused on specific end user categories are likely to be more successful than a single broadbrush strategy for all users."

Motivated by the need to better capture the complexity of human behaviour in technology decision-making, McCollum *et al.*[40] advanced the parameters of modelling consumer heterogeneity by representing 27 unique sub-groups in their global assessment of purchasing decisions for (low-carbon) light-duty vehicles.¶¶¶ Critically, by accounting for heterogeneous non-monetary attributes, it was observed that the market penetration of electric vehicles may be delayed for several decades.[40]

Subsequently, Desai *et al.*[196] constructed a model of personal vehicle preferences in the US, which suggested accounting for consumer heterogeneity would result in 23% higher market share for electric vehicles by 2040. Contrary to the findings of McCollum *et al.*,[40] the results implied a possibility for "cascading diffusion" of electric vehicles within the US market over the next two decades, while underscoring the implications of accounting for both domestic and international heterogeneity when formulating energy policies.[196] The dual focus is critical during the formative stage of the technological innovation system,[159,160] as niche markets develop and international learning curves drive prospects for deployment and diffusion,[203,204] as observed with hydrogen energy technologies.[205–207]

In the context of net-zero energy buildings in South Korea, Choi *et al.*[208] distinguished between 'forward-looking consumers', 'cost-sensitive consumers', and 'cost-insensitive consumers' to reflect heterogeneous preferences. Choi and colleagues[208] also reported the influence of socio-demographic factors on housing preferences, indicating the potential of "unobservable common determinants among individuals with similar characteristics." Based on the notion of heterogeneous strategic consumers introduced by Guo and Hassin,[209] Liu *et al.*[210] further demarcate between strategic and homogenous (*i.e.* myopic) consumers; analysing threshold scenarios in which strategic consumers opt for a low price, high 'greenness', or compare price and greenness before reaching a price threshold.

The notion of strategic and myopic consumer categories aligns to the inclusion of different levels of engaged (*i.e.* strategic) and non-engaged (*i.e.* myopic) consumers within this study. Notably, Liu and colleagues[210] reported that consumer heterogeneity influences the potential profitability of the low-carbon supply chain; underlining the need for effective subsidy schemes to support strategic consumer behaviour in promotion of supply chain sustainability.

Analysing the rebound effect in the Austrian context through a computable general equilibrium model, Kulmer and Seebauer[194] also emphasised the importance of accounting for household heterogeneity in view of divergent consumer preferences. Furthermore, based on survey data collected from 921 urban households in China, Lei *et al.*[192] illustrated how consumers have 'heterogeneous energy lifestyles', as reflected by different energy consumption habits and purchasing preferences for home appliances. In turn, the authors advocate for the notion of "common but differentiated household mitigation policies" to support the energy transition.[192]

In the context of the hydrogen economy, a focus on inter-group comparisons remains primarily limited to early exploration in the UK[43,52,80] and Australian contexts.[58,59] Insights from large datasets are constrained to examining the effects of gender and political party preferences in the Australian context[59] (see ESI11†). Although Bögel *et al.*[211] compared public attitudes towards hydrogen fuel cells across seven EU Member States, PLS-MGA is yet to be employed to derive more comprehensive findings on consumer heterogeneity at the national level.

The literature affirms that consumer decision-making processes can vary significantly across segments. Consequently, factoring heterogeneity into empirical studies is recommended to minimise the risk of bias results and invalid conclusions,[60,64] which could misdirect energy policy making. In turn, this study employs PLS-NC-MGA to comprehensively examine the scope for developing segment-specific policy strategies to support the domestic hydrogen transition. Following the literature review findings, different levels of technology and environmental engagement, in addition to socio-economic status, are operationalised into the modelling approach.

4 Hypotheses development

4.1 Safety perceptions

Based on a systematic review of 65 documents on the hydrogen economy since 2000, Almaraz and colleagues[53] found that only 14 studies engaged with (technological) safety,‖‖‖ which was the lowest ranking of 12 identified social aspects. This level of under-exploration is surprising given that safety is a prerequisite to both technical feasibility and public support,[53,212] which

§§§ Investigated the use and user perceptions of different information technologies among four groups in an engineering organisation: engineering managers, project engineers, professionals, and secretaries.

¶¶¶ Demarcated according to three dimensions: settlement pattern (urban, suburban, rural); adoption attitude (early adopter, early majority, late majority); and vehicle usage intensity (modest driver, average driver, and frequent driver).

‖‖‖ Defined by the authors[53] as "the condition of being protected from or unlikely to use danger, risks, or injury while producing, transporting, storing, distributing or using hydrogen products."

Table 2 Summary of findings on safety perceptions of domestic hydrogen

Study and year	Country context, sample size and methods	Key findings
Ref. 230 (2019)	• United Kingdom • $N = 39$ • In-person focus groups	• Respondents felt assured that stringent safety standards would be enforced prior to approving the use of hydrogen in domestic settings, which instilled a sense of confidence
Ref. 39 (2020)	• United Kingdom • $N = 700$ • Online survey	• Most online survey respondents perceived the impact of hydrogen homes appliances on safety to be neutral (68.9%), followed by positive (17.3%), and negative (13.9%)
	• $N = 102$ • Paper survey	• Paper survey respondents were more equally split between a neutral (57.4%) and positive perception (34.7%), while a minority of respondents expressed a negative perception of hydrogen safety (7.9%)
Ref. 23 (2020)	• United Kingdom • $N = 100$	• Safety risks were perceived to be significantly higher in the kitchen setting
	• Paper survey	• Gas hobs were seen to permeate domestic energy cultures, in view of their more tangible socio-material qualities compared to 'out-of-sight' gas boilers
Ref. 58 (2022)	• Australia • $N = 2785$ • Online survey	• Respondents expressed high levels of trust ($M = 4.11$, $SD = 0.92$) that adequate safety precautions would be put in places to keep risks under control should a national hydrogen economy develop (as measured via a five-point Likert scale)
Ref. 52 (2023)	• United Kingdom • $N = 58$	• Respondents expressed more confidence in the safety credentials of induction hobs as opposed to gas hobs
	• Online focus groups	• Safety assurances in the context of hydrogen cooking may prove critical to fuel stressed households, especially when composed of young families
Ref. 47 (2023)	• United Kingdom • $N = 1064$ • Online survey	• Safety risks ($N = 64$) were cited 4.5 times more frequently than safety benefits ($N = 14$), while other respondents expressed a more neutral perception ($N = 26$)

justifies the inclusion of safety perceptions in hydrogen acceptance studies (see Table 2). Other literature review results suggest safety perceptions will shape prospects for the domestic hydrogen transition,[78] ranking as a 'significant' factor when compared to 13 other acceptance indicators.[48] Interestingly, among Dutch respondents, males had a higher perception of safety risks associated with flammability,[213] suggesting potential divergence between genders or sub-groups of the population (*i.e.* technology engaged citizens).

Public perceptions of hydrogen safety may hinge firmly on mainstream media reports,[214] which can sometimes skew towards a negative social representation,[215] whereby explosive and catastrophic imagery[216] may permeate the public imagination[163,217,218] Relatedly, in the wider context of energy issues and climate change, Stoutenborough and Vedlitz[219] observe how public perceptions of risk are often confined to media-constructed parameters. This study seeks to mitigate perception bias by asking respondents to evaluate the safety of hydrogen in comparison to natural gas, which mirrors the notion that "public participation is needed to guarantee a fair and transparent evaluation of hydrogen *vs.* other fuels."[53] Parallel research suggests an underlying positive perception of hydrogen safety, which is significant in shaping social acceptance ($\beta = 0.058$, $p = 0.004$)[120] and driving perceived adoption potential (0.193, $p < 0.001$).[68]

Beyond the constraints of media-constructed parameters,[219] Beasy *et al.*[163] argue that technical knowledge can support positive perceptions of hydrogen safety to support social acceptance. However, the ability to access or absorb technical information may be constrained by opportunities for directly experiencing hydrogen technologies,[220,221] and may diverge according to a range of socio-structural variables such as education level.[222] Such dynamics give rise to potential divergence regarding safety perceptions, as documented in mixed-method analyses on hydrogen acceptance.[47,52]

The prospect of transitioning to hydrogen homes may elicit concerns over safety risks,[23,52] which could provoke feelings of fear and dread, as observed with other hydrogen energy technologies such as fuel cell vehicles and fuelling stations.[119,223,224] Qualitative responses in the UK context highlight a mix of fears and discomfort,[47,216] attributed primarily to the flammable nature of hydrogen gas.[225] In extreme instances, consumers associate hydrogen with nuclear power, citing disaster and devastation as the common denominator.[47,226]

Despite its risk profile, hydrogen also presents some benefits such as the elimination of carbon monoxide poisoning in the residential environment.[227] Interestingly, evidence suggests that consumers with a high level of technology and environmental engagement may be more attuned to both the safety risks and benefits of domestic hydrogen.[47] Nevertheless, underlying risk perceptions[39,228,229] may prevent consumers from undertaking more in-depth safety evaluations, which threatens to constrain domestic hydrogen acceptance. Safety perceptions of gas-based and electric-powered cooking technologies may also diverge.[23,59] Accounting for the foreseeable influence of safety perceptions on prospects for deploying hydrogen homes (see Table 2), the following hypotheses are developed:

H1a: Safety perceptions will positively influence the perceived adoption potential of hydrogen homes across consumer sub-groups of the UK population.

H1b: Consumer sub-groups of the UK population will have heterogenous safety perceptions regarding the prospective transition to hydrogen homes.

H1c: A positive safety perception of domestic hydrogen relative to natural gas is a necessary condition for enabling perceived adoption potential for hydrogen homes across consumer sub-groups of the UK population.

4.2 Technology perceptions

The performance aspects of new energy technologies such as HFCVs[220,231,232] must be viewed favourably to accelerate the low-carbon energy transition.[233] Several contributions to the literature document the importance of technology performance as a driver of market adoption,[234–237] however, few studies have analysed consumer perceptions regarding the functionality of hydrogen boilers and hobs (see Table 3). By contrast, other acceptance constructs such as environmental perceptions and perceived risks have received significantly more attention in wider studies on hydrogen acceptance.[78]

The importance of brand familiarity has been emphasised for consumer durables such as such as heating, ventilation, and air-conditioning appliances[238] and appears a relevant factor in the context of hydrogen home appliances,[80] as detailed in Table 3. However, a wider evidence base highlights the critical importance of perceived technology attributes[239] across a wide range of products[240,241] and national contexts,[242] such as solar PV adoption in the Netherlands,[243] energy efficiency lighting in Malaysia,[244] and smart home technologies in the US.[245] Crucially, sustainable energy technology acceptance in the residential context is higher when performance benefits are easily discernible,[246] underscoring the need for hydrogen appliances to demonstrate a relative advantage over existing boilers and hobs.[78]

Notably, research suggests that consumers with high levels of innovativeness are more likely to derive satisfaction from adopting new energy technologies such as smart thermostats.[179] Moreover, Lozano *et al.*[58] reported a positive association between self-perceived early adopters of energy technologies (*i.e.* 'innovators') and hydrogen acceptance. In the Chinese context, Zha *et al.*[247] identified four specific consumer segments which should be accounted for when targeting policy interventions to accelerate technology diffusion for energy efficient appliances. Critically, respondents belonging to the lowest income group, which can be taken as a proxy for experiencing fuel stress, attributed most importance to energy efficiency and had the highest tendency for energy conservation in view of potential cost savings.[247] However, research conducted in the UK[23,39,52] is yet to substantiate whether such a finding may transmit to the context of hydrogen homes.

It is also probable that technology perceptions may vary according to appliance type (see Table 3), as reported in the case of energy efficient air conditioners and refrigerators in India.[248] Examining consumer acceptance for energy efficient refrigerators and washing machines, Zha *et al.*[247] highlighted the need to evaluate other appliances including cooking technologies (*e.g.* rice cookers in China) for deeper comparative insights. Notably, a recent narrative literature review ranked the lived experience of hydrogen cooking as a potentially 'major'**** factor among other social acceptance constructs, whereas the lived experience of hydrogen heating ranked as a 'minor' factor,[48] in line with the study of Scott and Powells.[23]

Qualitative results from one UK study highlighted potential divergence in consumer perceptions towards hydrogen heating and cooking technologies.[52] Nevertheless, respondents demonstrated similar levels of adoption potential when answering poll questions on a five-point Likert scale,[52] which also proved the case in the Australian context.[58] In view of the need to comprehend technology perceptions at the early stage of the hydrogen transition, this study also accounts for perceptions towards hydrogen cooking appliances,[52] which has remained largely overlooked in prior research due to a primary focus on hydrogen boilers.[51,249,250] The following hypotheses are formulated, as supported by the inclusion of a reflective-formative construct,††††[104] in the proposed model:

H2a: The perceived performance of hydrogen boilers will have a positive influence on technology perceptions for hydrogen homes across consumer sub-groups of the UK population.

H2b: The perceived performance of hydrogen hobs will have a positive influence on technology perceptions for hydrogen homes across consumer sub-groups of the UK population.

H2c: Technology perceptions will have a positive influence on the perceived adoption potential of hydrogen homes across consumer sub-groups of the UK population.

H2d: Consumer sub-groups of the UK population will have heterogenous perceptions of hydrogen boiler performance.

H2e: Consumer sub-groups of the UK population will have heterogenous perceptions of hydrogen hob performance.

H2f: Consumer sub-groups of the UK population will have heterogenous technology perceptions of domestic hydrogen appliances.

H2g: A positive technology perception is a necessary condition for enabling perceived adoption potential for hydrogen homes across consumer sub-groups of the UK population.

4.3 Financial perceptions

The broader literature on hydrogen energy acceptance,[252,253] including studies on HFCVs,[254] highlights the importance of economic factors[255] and associated financial perceptions.[252,253] These observations are consistent with studies on low-carbon energy technologies, which find financial factors to be a critical barrier to consumer acceptance,[256] as highlighted in the context of residential decarbonisation in the UK.[257] For example, it is well documented that cost factors remain a critical barrier to deploying domestic micro-generation technologies to support residential decarbonisation.[258,259]

Affordability concerns associated with transitioning to domestic hydrogen appliances have been recorded prior to the

**** The study employed five categories of importance: critical, major, significant, moderate, minor.[48]

†††† Higher order constructs can support theoretical parsimony and reduce model complexity.[433]

Table 3 Summary of findings on technology perceptions of domestic hydrogen

Study and year	Country context, sample size and methods	Key findings
Ref. 251 (2018)	• Australia • $N = 2785$ • Online survey	• Female respondents registered higher levels of concern over risks associated with changes to the 'lived experience' of cooking
Ref. 39 (2020)	• United Kingdom • $N = 700$ • Online survey • $N = 102$ • Paper survey	• Most online survey respondents perceived the impact of hydrogen homes appliances on energy performance to be neutral (63.1%), followed by positive (32.3%), and negative (4.6%) • Paper survey respondents were more equally split between a neutral (50.0%) and positive perception (45.1%), while a minority of respondents expressed a negative perception of hydrogen safety (4.9%)
Ref. 58 (2022)	• Australia • $N = 906$ • Online survey	• Consumers reported the same level of support for using hydrogen for cooking, as for space heating ($M = 3.60$) • Support for using hydrogen for hot water proved marginally higher ($M = 3.71$), as measured on a five-point Likert scale
Ref. 52 (2023)	• United Kingdom • $N = 58$ • Online focus groups	• Consumers either believed or hoped that hydrogen appliances should offer an upgrade in terms of efficiency and smartness
Ref. 80 (2023)	• United Kingdom • $N = 58$ • Online focus groups	• Product performance and product range ranked among the top tier variables behind preferences for buying an established brand
Ref. 83 (2023)	• United Kingdom • $N = 1064$ • Online survey	• Performance benefits (i.e. efficiency or utility benefits) of hydrogen appliances ranked eighth out of 17 positive sub-factors of domestic hydrogen acceptance • Performance benefits ($N = 35$) were cited four times more frequently than performance losses ($N = 9$), and cited most frequently by respondents with a high level of technology and environmental engagement

cost-of-living crisis,[260,261] while follow-up work suggests financial costs rank as a 'critical' acceptance factor.[48] Given existing constraints on household finances, Thomas *et al.*[250] assert that social resistance is likely to arise if residential decarbonisation leads to a rise in UK energy bills. Similarly, Calvillo *et al.*[50] concluded that policy makers would need to ensure that the costs of hydrogen are comparable to gas for incentivising consumer adoption.

Divergence in financial perceptions has been documented in a recent UK study with online focus groups ($N = 58$). Foremost, fuel stressed respondents were cautious of hydrogen leading to a further hike in energy bills, which was viewed untenable even if motivated for long-term environmental and energy security purposes.[80] Relatedly, the risk of household energy vulnerability has been stressed in the context of Australia's domestic hydrogen transition.[51] By contrast, environmentally conscious UK citizens emerged as an outlier, instead conveying a degree of willingness to pay higher bills in promise of a greener (hydrogen) future,[80] which supports other findings.[43,262] Overall, it follows that adverse macro-economic conditions could significantly stifle prospects for transitioning to hydrogen homes.

Based on a comprehensive typology identifying 48 specific factors of domestic hydrogen acceptance *via* qualitative coding, perceived financial risks ranked third in terms of explaining variance between consumer sub-groups.[47] Critically, evidence shows that concerns are strongest among baseline and fuel stressed respondents.[47,80] It follows that consumers may have divergent financial perceptions according to their socio-economic circumstances, as well as their environmental beliefs. Recent studies conducted in China[192,210] further highlight the relevance of interactions between consumer heterogeneity and market acceptance.[263,264] For example, Lei *et al.*[192] found that distinct household groups, clustered by income and age, have different sensitivities to the same energy policies, which influences purchasing preferences for air-conditioners. Additionally, Liu *et al.*[210] describe how 'strategic' consumers may delay their purchasing decisions for new technologies in anticipation of potential cost savings as the market develops. Based on multi-year (2012–2017) data collected in California, Lee and colleagues[265] identified four heterogeneous clusters of early adopters for plug-in electric vehicles according to income level and housing tenure status.‡‡‡‡

In addition to informing the dynamics of market acceptance for hydrogen homes,[38,48] insights on financial perceptions can help support wider national energy transitions[204,266] by supporting the evidence base on willingness to pay for green energy technologies.[267,268] In response, the following hypotheses are proposed to examine the influence of financial perceptions (see Table 4) and the potential for heterogeneous decision-making:

‡‡‡‡ The latent class model demonstrated strong variation in market diffusion dynamics up to 2030.

Table 4 Summary of findings on financial perceptions of domestic hydrogen

Study and year	Country context, sample size and methods	Key findings
Ref. 257 (2023)	• United Kingdom • $N = 1551$ • Online survey	• In winter 2022, the government's public attitudes tracker (PAT) reported concerns about the cost of installation (45%) as the main barrier to changing to a low carbon heating system • Concerns about running costs were cited by 25% of respondents
Ref. 269 (2019)	• United Kingdom • $N = 742$ • Online survey	• Affordability concerns represented the most significant barrier to domestic hydrogen adoption for citizens living in socio-economically deprived areas of the north of England
Ref. 80	• United Kingdom • $N = 58$ • Online focus groups	• Few consumers expect hydrogen appliances would be cheaper to purchase compared to traditional boilers and hobs • The wider majority are somewhat optimistic that price parity might be delivered which was also broadly the case for energy bills, whereas around one-third of respondents predict higher costs
Ref. 58	• Australia • $N = 906$ • Online survey	• Respondents had a neutral perception of willingness to pay for the use of hydrogen technologies ($M = 3.089$, SD = 1.008) as measured on a five-point Likert scale
Ref. 47 (2023)	• United Kingdom • $N = 1845$ • Online survey	• Perceived financial risks ranked as the third most critical factor, whereas perceived financial benefits ranked 28th among 48 sub-factors

H3a: Financial perceptions of hydrogen homes appliances will have a negative influence on the perceived adoption potential of hydrogen homes across consumer sub-groups of the UK population.

H3b: Consumer sub-groups of the UK population will have heterogenous financial perceptions regarding the prospective transition to hydrogen homes.

4.4 Perceived socio-economic costs

The implications of the current energy crisis[270,271] and associated cost-of-living crisis[260,272] – including potential ramifications for domestic energy futures in countries such as the UK[261,273] – are far-reaching. Nevertheless, public perceptions of energy technologies such as hydrogen are seldom contextualised within the broader socio-economic context.[79]

Almaraz *et al.*[53] found that socio-economic factors were explored in just one-third of retrieved studies on social aspects of the hydrogen economy, while Scovell[253] and Dumbrell[274] emphasised the need to account for perceived socio-economic costs in hydrogen acceptance studies. This notion is also reflected in the broader literature on technology acceptance,[275] including studies on domestic energy technologies such as solar PV and smart homes.[78]

Prior to the cascading effects[271,276] of the COVID-19 pandemic[277,278] and ongoing Russo-Ukrainian War,[279–281] survey results from the North of England ($N = 700$) suggested residents had a mostly neutral perception of socio-economic impacts related to the hydrogen switchover.[39] More recent longitudinal data from the PAT underlines the extent to which public concerns over energy insecurity and fuel stress prevail in the wider UK context.[282] Post-pandemic hydrogen studies conducted in the UK[47,80] also flag significant concerns of energy injustice,[283,284] principally distributional[285,286] and procedural injustice.[287,288] For example, following online focus groups, energy justice concerns were cited most frequently by fuel stressed participants and citizens with a high level of environmental engagement.[80]

Moreover, subsequent evidence suggests concerns over fairness and equity strongly influence the dynamics of domestic hydrogen acceptance.[47] Critically, worries related to a potential choice deficit concerning the transition to hydrogen homes registered highest among fuel stressed respondents.[47] By contrast, the same variable failed to register for consumers with the highest level of technology and environmental engagement.[47] Similar dynamics were observed when considering the impact of domestic hydrogen on the cost-of-living crisis, suggesting degrees of consumer heterogeneity towards perceived socio-economic costs.[47]

In July 2023, the UK Minister for Energy Efficiency and Green Finance, Lord Callanan, announced the cancellation of a planned trial for hydrogen homes in Whitby village (Northwest England),[289] following local resistance and concerns over a lack of community benefits.[290,291] A lack of social acceptance likely reflects associated socio-economic concerns at the macro-level, as communicated by communities in the North of England[39] and reinforced by fuel stressed respondents living in industrial towns.[80]

Notably, approximately 10.3% of the Whitby population experience fuel poverty,[292] while the surrounding area of Ellesmere Port ranks within the top 8% most deprived areas in England, according to the 2019 English Indices of Deprivation (IoD).[293] Subsequently, amid further controversy, a proposed trial for Redcar (Northeast of England) was rejected in December 2023, casting increasing doubts over the role of hydrogen homes in residential decarbonisation.[294,295] Although potential socio-economic benefits are envisioned by the UK government in terms of job growth and generation of gross value added from the hydrogen economy[18] which may trickle down to local communities,[296] the current economic climate is largely shrouded in instability and pessimism.§§§§[297,298]

In October 2023, the NIC concluded that a domestic hydrogen decarbonisation pathway would entail similar levels of national economic activity compared to an electricity-based transition.[31] Furthermore, Hoseinpoori *et al.*[32] found that the total system transition cost would be similar in both scenarios. Nevertheless, the sizeable investment cost and complexity of converting the gas grid to hydrogen constrain the techno-economic feasibility of deploying hydrogen homes at scale.[34,79,299] Moreover, UK, European, and global assessments suggest a limited role for domestic hydrogen in a cost-optimal decarbonisation pathway,[35] which may induce heightened socio-economic concerns.

Against this backdrop, it is evident that consumer perceptions of macro-economic impacts will prove context-dependent and place-specific. In response, this study explores how consumers perceive potential socio-economic risks related to national energy insecurity and fuel poverty, which are explored through two hypotheses focused on perceived socio-economic costs:

H4a: The perceived socio-economic costs of transitioning to hydrogen homes will have a negative influence on the perceived adoption potential of hydrogen homes across consumer sub-groups of the UK population.

H4b: Consumer sub-groups of the UK population will have heterogenous perceptions regarding the socio-economics costs of transitioning to hydrogen homes.

4.5 Production perceptions

Research shows that public perceptions of specific energy technologies can vary significantly between countries[300] and at the sub-national level.[198] For example, Doran *et al.*[300] found energy efficient appliances and energy efficient houses were viewed relatively favourably by both German ($N = 142$) and Norwegian students ($N = 106$),¶¶¶¶ whereas carbon capture and storage (CCS) received less support (Germany: $M = 4.48$; Norway: $M = 5.67$), which may infer opposition to 'blue' hydrogen (*i.e.* steam methane reformation with CCS).[43]

Focusing on onshore wind power, Gölz and Wedderhoff[301] applied PLS-MGA to compare social acceptance at the sub-national level ($N = 2009$), with Southern Germany presenting the highest rate of rejection to onshore wind turbines, whereas acceptance was strongest in Northern Germany. In the UK context, based on analysis of national survey data collected between 2012 and 2018, Roddis *et al.*[198] demonstrated that solar energy received the highest acceptance level ($M = 80.1$), followed by renewable energy in general ($M = 76.8$), whereas nuclear ($M = 37.1$) and fracking ($M = 22.1$) received the lowest approval rates.

Reviewing international evidence on public perceptions of energy transition pathways,[300] alongside emerging evidence on hydrogen production technologies[302,303] and perceived environmental benefits,[47] is instructive to the case at hand. Specifically, the UK government is targeting a 'twin-track' production approach, which aims to leverage benefits from a blue pathway, alongside a renewable-based (*i.e.* green) pathway using electrolysis.[18] To date, one small-sample study ($N = 58$) has engaged directly with this area, showing 39% and 46% of respondents to be very and somewhat supportive of the twin-track strategy, respectively.[43] However, it emerged that environmentally engaged citizens were more likely to question the credentials of blue hydrogen,[43] mirroring critiques in the scientific literature.[304–306]

Consequently, the twin-track approach was least supported among environmentally engaged respondents, whereas fuel stressed participants living in industrial towns expressed the highest level of support, in hope of a more secure and sustainable energy future.[43] Additionally, engagement in renewable energy technology strengthened support for the twin-track strategy.[43]

Subsequent research found that environmental benefits were cited more frequently among fuel stressed respondents compared to the baseline group, inferring a higher degree of optimism for a clean energy future.[47] This pattern may reflect the high propensity for old and inefficient boilers within fuel poor homes, aggravating concerns over environmental impacts, as well as safety and costs.[52] For example, in the case of Whitby village and the surrounding region of Ellesmere Port, it is documented that over 80% of homes have an Energy Performance Certificate (EPC) rating between D–G,[292] which may motivate interest in securing efficiency gains and environmental benefits.

Overall, the international literature (see Table 5) suggests public support for green hydrogen production will likely trump other pathways,[58,296,303,307] and may be coupled to perceptions of synergistic benefits for cross-sectoral decarbonisation.[308,309] Against this rich background, two additional hypotheses are examined to extend the scope of inquiry:

H5a: Production perceptions will have a positive influence on the perceived adoption potential of hydrogen homes across consumer sub-groups of the UK population.

H5b: Consumer sub-groups of the UK population will have heterogenous production perceptions regarding the prospective transition to hydrogen homes.

H5c: Support for green and blue hydrogen production pathways is a necessary condition for enabling perceived adoption potential for hydrogen homes across consumer sub-groups of the UK population.

4.6 Perceived adoption potential

At the market level, sustainable consumer behaviour – which may manifest directly through low-carbon energy adoption[311] – broadly involves purchasing products which account for environmental, societal, and fair-trade concerns.[312] Consequently, sustainable consumption in the marketplace entails an environmental and socio-economic dimension. Parallel research shows that domestic hydrogen acceptance positively mediates the relationship between perceived community benefits and willingness to adopt domestic hydrogen ($\beta = 0.173, p < 0.001$).[313]

§§§§ By contrast, the Australian public has a more positive outlook towards potential economic and energy security benefits from the hydrogen economy[58,84,163] in view of the country's significant export potential to markets such as Japan and South Korea.[434,435]

¶¶¶¶ German response: $M = 6.01$, $M = 6.54$; Norwegian response: $M = 6.36$, $M = 6.95$.

Table 5 Summary of findings on production perceptions of domestic hydrogen

Study and year	Country context, sample size and methods	Key findings
Ref. 296 (2019)	• United Kingdom • $N = 578$ • Online survey	• Respondents expressed a stronger preference for green hydrogen over blue hydrogen, as reflected by mean scores of 82/100 and 59/100
Ref. 39 (2020)	• United Kingdom • $N = 700$ • Online survey • $N = 102$ • Paper survey	• Most online survey respondents perceived the impact of hydrogen homes appliances on the environment to be positive (69.9%), or otherwise neutral (26.6%) • Paper survey respondents had similar perceptions, split between 69.3% positive, 23.8% neutral, and 6.9% negative
Ref. 58 (2022)	• Australia	• Respondents expressed higher levels of support for producing hydrogen from renewable energy and electrolysis only ($M = 3.63$, SD = 0.82)
	• $N = 2785$	• Support for using fossil fuels with CCS as an intermediate step while transitioning to renewables was comparatively lower ($M = 3.18$, SD = 0.91)
	• Online survey	• Respondents partially agreed that hydrogen contributed to climate change protection ($M = 3.51$, SD = 0.85), as measured on a five-point Likert scale
Ref. 303 (2023)	• Norway • $N = 1906$ • Online survey	• Norwegian citizens favoured green hydrogen ($M = 3.90$) over blue hydrogen ($M = 3.20$) and grey hydrogen ($M = 2.30$), as measured on a five-point acceptance scale
Ref. 47 (2023)	• United Kingdom • $N = 1064$ • Online survey	• Respondents with moderate and high levels of technology and environmental engagement made most references to environmental benefits
Ref. 310	• Germany • $N = 2054$ • Online survey	• Respondents expressed openness towards local use of green hydrogen, with strong expectations for environmental benefits

Furthermore, it should be highlighted that the observed effect was strongest among the ten exogenous constructs included in the model.[313]

In a broad sense, 'perceived adoption potential' can be operationalised through SEM to measure the feasibility that an individual consumer will adopt a given technology according to the influence of specific factors.[314] This study leverages prior developments in the literature (see ESI12†) by developing a specific measure of perceived adoption potential, which combines adoption willingness (PAP1–PAP3) and perceived community benefits (PAP4–PAP6) to form a comprehensive endogenous construct, composed of six indicators. The novelty of this approach lies in capturing interrelated aspects of behavioural and community acceptance.

Notably, a threefold focus on perceived community benefits is reflected in evidence submitted by Cadent Gas[292] to the UK government as part of the hydrogen heating village trial application, which specified economic, social, and environmental gains envisioned *via* the local trial in Whitby.|||||||| Crucially, perceptions related to community benefits will shape local and broader socio-political acceptance,[48] in addition to influencing the potential for domestic hydrogen adoption.[23,52]

Through the inclusion of indicators measuring perceived community benefits at the economic (PAP4), social (PAP5), and environmental level (PAP6), the proposed construct adheres firmly to the scientific convention of employing at least three measurement items.[315] In doing so, this study overcomes prior approaches in the context of household energy adoption. For example, Sopha and Klöckner[316] measured adoption intention for wood pellet heating *via* two indicators,***** while a subsequent study on biomass heating adoption employed one indicator.†††††[317] Similarly, the study of Gölz and Wedderhoff[301] relied on a single indicator to measure onshore wind energy acceptance in Germany.

5 Conceptual framework

In a seminal contribution focused on consumer decision-making for residential energy use, Wilson and Dowlatabadi[318] emphasised the importance of context, scale, and heterogeneity in advocating for integration between social psychology, sociology, conventional economics, behavioural economics, and technology diffusion models. Additionally, Michelsen and Madlener[319] integrated technological, psychological, economic, and non-economic factors to examine homeowners' preferences for an innovative residential heating system. More recently, McCollum *et al.*[40] demonstrated the efficacy of modelling

|||||||| Including tackling fuel poverty, high air pollution, social isolation, and digital exclusion (social); growing the local economy, job creation, and upskilling the existing local workforce (economic); and future-proofing local consumers' homes in the transition to low-carbon heat (environmental).[292]

*****Agreement level with the following statements: (1) when I decide next time for a new heating system, my intention to use wood pellet heating is strong; and (2) I intend to use wood pellet heating.[316]

††††† *i.e.* Rate your degree of agreement or disagreement with the following statement: I would be willing to buy biomass heating in the near future.[317]

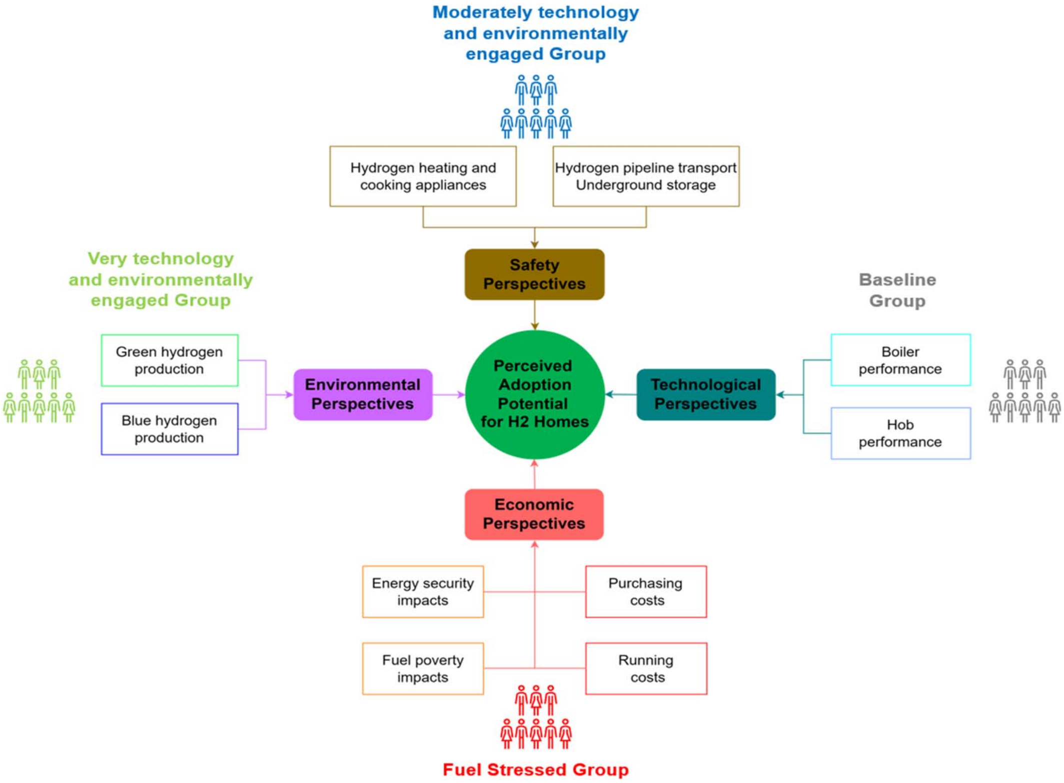

Fig. 7 The Safety-Technological-Economic-Environmental Perspectives (STEEP) Framework applied to multigroup analysis.

constructs such as environmental concern, technology perceptions, and behavioural practices when examining heterogeneous preferences for low-carbon transportation, Drawing on this dataset, the mediating role of domestic hydrogen acceptance in predicting willingness to adopt domestic hydrogen appliances has been explored.[313] In addition to perceived community benefits ($\beta = 0.173$, $p < 0.001$), production perceptions ($\beta = 0.133$, $p < 0.001$), perceived socio-economic costs ($\beta = -0.036$, $p = 0.001$), and safety perceptions ($\beta = 0.037$, $p = 0.004$) had statistically significant indirect effects on willingness to adopt domestic hydrogen before 2030,[313] reflecting the presence of complementary partial mediation in the model.[320,321] While the Domestic Hydrogen Acceptance Model (DHAM) presents critical insights on multiple dimensions,[120,313] adoption dynamics for hydrogen homes may rest firmly on technology and financial perceptions.

This analysis expands the analytical lens through an explicit focus on the safety, technological, economic, and environmental dimensions of perceived adoption potential for hydrogen homes.[68] The specified dimensions are of critical importance to the energy transition, as specified within the UK Hydrogen Strategy.[18] Synergies between techno-economic, technical, market, political and social dimensions are required to scale up of the hydrogen economy,[79] which will rest on several levers: realising 10 GW of low-carbon hydrogen production by 2030; developing safe and reliable network infrastructure for large-scale hydrogen transport and storage; securing a competitive economic advantage within the global hydrogen market; and accelerating green growth and cross-sectoral decarbonisation.[18] In response, Fig. 7 internalises the call for an integrated perspective while introducing a built-in multigroup focus, as reflected by the inclusion of four distinct consumer segments.

6 Results

This section reports the results of the analysis in five stages. Firstly, Section 6.1 relays the descriptive findings and preliminary insights from a series of K–W tests. Section 6.2 describes the measurement model assessment, while Section 6.3 outlines the three-step MICOM procedure. Next, Section 6.4 compares the structural models for each pairwise comparison, while Section 6.5 extends the MGA by conducting an IMPA to derive strategic insights for segment-specific consumer engagement. Lastly, Section 6.6 makes a novel contribution through the addition of NC-MGA.

6.1 Descriptive statistics and results from analysis of variance

6.1.1 Perceived adoption potential. Overall, from a maximum possible score of 60, the VEG showed a moderately high level of perceived adoption potential ($M = 43.3$), while the BLG demonstrated the least potential ($M = 33.9$). Meanwhile, the MEG ($M = 37.6$) placed above the sample mean ($M = 37.0$), whereas the FSG fell slightly below this value ($M = 36.0$). The descriptive results suggest that technology and environmental engagement, and to a lesser extent fuel stress, are potential drivers of domestic hydrogen adoption.

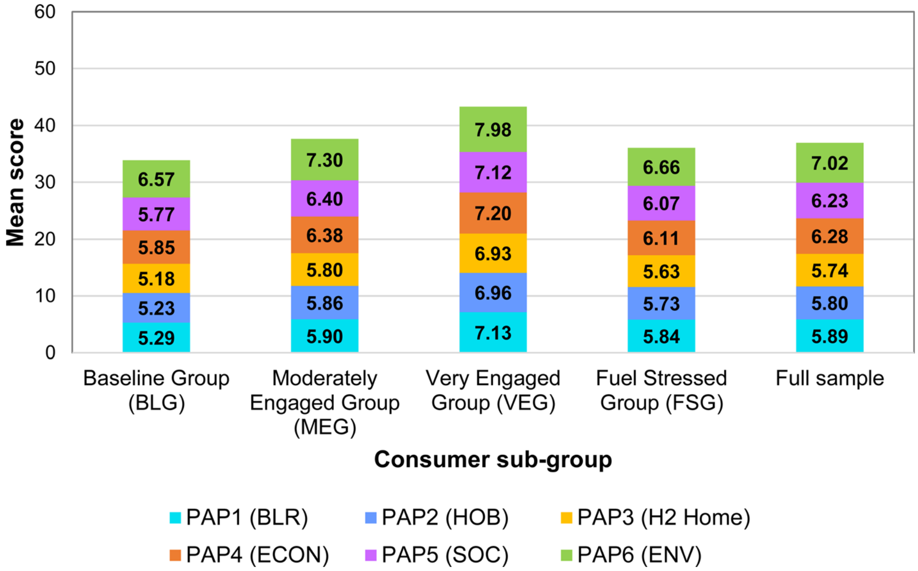

Fig. 8 Perceived adoption potential for hydrogen homes across consumer sub-groups. PAP1 = willingness to adopt a hydrogen boiler; PAP2 = willingness to adopt a hydrogen hob; PAP3 = willingness to adopt a hydrogen home; PAP4 = perceived economic benefits; PAP5 = perceived social benefits; PAP6 = perceived environmental benefits.

Foremost, as reflected in Fig. 8 and 9, the VEG demonstrates a more positive outlook across all indicators, resulting in the following rank order: (1) VEG: $M = 7.22$; (2) MEG: $M = 6.27$; (3) FSG: $M = 6.01$; (4) BLG: $M = 5.65$. For PAP indicators 1–3 (hydrogen boiler, hydrogen hob, hydrogen home), the following scores are reported: VEG: $M = 7.01$; MEG: $M = 5.85$; FSG: $M = 5.73$; BLG: $M = 5.23$. The same rank order is retained when considering PAP indicators 4–6 representing perceived community benefits (economic, social, environmental): VEG: $M = 7.43$; MEG: $M = 6.69$; FSG: $M = 6.28$; BLG: $M = 6.06$.

Consequently, statistically significant differences are detected between all pairwise comparisons at the 1% level (see Table 6) excluding the MEG and FSG ($\rho = 0.205$, $r = 0.07$). The largest difference is observed between the VEG and BLG ($r = 0.47$), followed by the VEG and FSG ($r = 0.38$). The remaining comparisons rank as follows: MEG–VEG ($r = 0.30$); MEG–BLG ($r = 0.20$); BLG–FSG ($r = 0.12$). In view of this rank order, a high level of technology and environmentally engagement is a significant factor in explaining differences in perceived adoption potential for hydrogen homes. However, the prospect of adopting hydrogen heating and cooking to live in a 'hydrogen

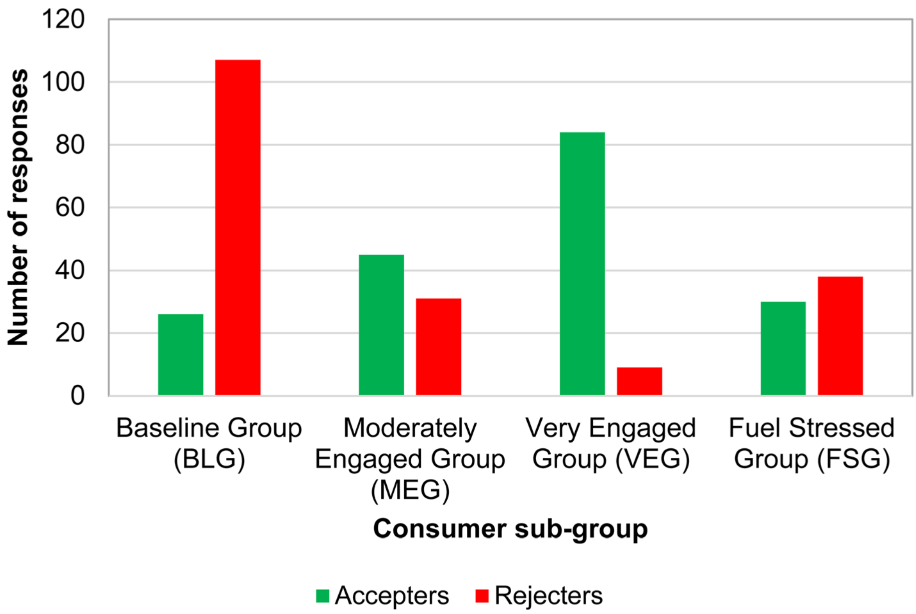

Fig. 9 Breakdown of hydrogen acceptance and rejection by consumer sub-group.

Table 6 Pairwise comparisons for perceived adoption potential[a]

	BLG	MEG	VEG	FSG
BLG				
MEG	<0.001*** (0.20)			
VEG	<0.001*** (0.47)	<0.001*** (0.30)		
FSG	0.001*** (0.12)	0.205 (0.07)	<0.001*** (0.38)	

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

home' fails to strengthen consumer acceptance, as illustrated in Fig. 8.

Further evidence highlighting the divergence between consumer sub-groups is strongly reflected in Fig. 9, which displays the top 10% of responses supporting and rejecting hydrogen, based on the metrics presented in Fig. 8 ($N = 185$ for outright 'accepters'; $N = 185$ for outright 'rejecters' (see ESI12†). The results clearly demonstrate that the VEG expresses the strongest level of support for domestic hydrogen, while the BLG represents the most resistant segment. Meanwhile, the MEG is somewhat positively skewed in its attitude towards hydrogen homes in this context (*i.e.* considering two extreme tails of attitude), while the FSG is somewhat negatively skewed.

6.1.2 Predictors of perceived adoption potential. Descriptive statistics show that safety, technological, economic, and environmental perspectives differ according to levels of engagement in technology and the environment. The observed patterns are highly consistent across the metrics shown in Fig. 9, whereby the VEG displays the most supportive response across all positive metrics – safety perceptions (SP), perceived boiler performance (BLR), perceived hob performance (HOB), and production perceptions (PP) – followed by the MEG. Furthermore, across each of these metrics, the FSG is marginally more supportive than the BLG. Foremost, the data suggests technology and environmental engagement is positively associated with support for the twin-track approach. Additionally, all sub-groups have an expressed preference for hydrogen heating; providing strong evidence that hydrogen boilers are the more favoured technology.

In terms of negative constructs – financial perceptions and perceived socio-economic costs – the previous sequencing (*i.e.* VEG, MEG, FSG, BLG) diverges in both cases. For financial perceptions, the BLG holds the most negative position, followed by the MEG, FSG, and VEG. However, for perceived socio-economic costs, the FSG has the highest level of concern, followed by the BLG, VEG, and MEG (see Fig. 10). Although the evidence suggests that technology and environmental engagement is associated with lower economic concerns, this trend could be due to socio-demographic factors such as annual income, which is partially inferred by the FSG having the strongest macro-economic concerns in relation to fuel poverty and energy insecurity.

Based on the preliminary descriptive and statistical analyses, production perceptions corresponds to the construct with the most variance across the sub-groups (SD = 0.60, $t = 207.36$, $p < 0.001$), followed by safety perceptions (SD = 0.45, $t = 85.97$, $p < 0.001$). Thereafter, the sub-constructs of technology perceptions present medium levels of variance: perceived boiler performance: SD = 0.31, $t = 31.570$, $p < 0.001$; perceived hob performance: SD = 0.37, $t = 49.12$, $p < 0.001$. Finally, constructs composing the economic dimension present comparatively less variance: financial perceptions: SD = 0.22, $t = 29.93$, $p < 0.001$; perceived socio-economic costs: SD = 0.20. $t = 10.54$, $p = 0.014$.

Ahead of conducting PLS-MGA, it is suggested that the environmental dimension of perceived adoption potential has

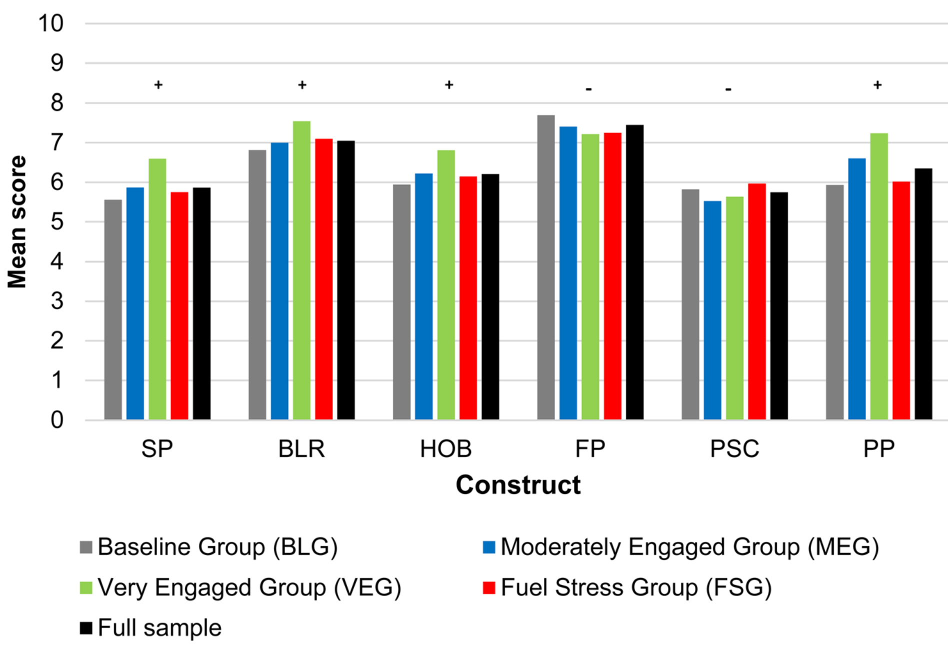

Fig. 10 Descriptive results for perceived adoption potential constructs across consumer sub-groups. SP = Safety Perceptions; BLR = Perceived Boiler Performance; HOB = Perceived Hob Performance; FP = Financial Perceptions; PSC = Perceived Socio-economic Costs; PP = Production Perceptions. Positive constructs are denoted by a plus sign (+). Negative constructs are denoted by a minus sign (–).

Table 7 Kruskal–Wallis H Test results for constructs predicting perceived adoption potential[a]

	BLG	MEG	VEG	FSG
Safety perceptions				
BLG				
MEG	<0.021** (0.09)			
VEG	<0.001*** (0.29)	<0.001*** (0.22)		
FSG	0.556 (0.05)	1.000 (0.03)	<0.001*** (0.25)	
Perceived boiler performance				
BLG				
MEG	0.344 (0.06)			
VEG	<0.001*** (0.18)	0.002*** (0.13)		
FSG	0.081 (0.08)	1.000 (0.02)	0.025** (0.11)	
Perceived hob performance				
BLG				
MEG	0.044 (0.08)			
VEG	<0.001*** (0.22)	<0.001*** (0.15)		
FSG	0.713 (0.05)	1.000 (0.03)	0.001*** (0.18)	
Financial perceptions				
BLG				
MEG	<0.001*** (0.10)			
VEG	<0.001*** (0.14)	0.985 (0.05)		
FSG	<0.001*** (0.13)	1.000 (0.04)	1.000 (0.01)	
Perceived socio-economic costs				
BLG				
MEG	0.320 (0.06)			
VEG	0.095* (0.08)	1.000 (0.02)		
FSG	1.000 (0.02)	0.179 (0.08)	0.056* (0.10)	
Production perceptions				
BLG				
MEG	<0.001*** (0.23)			
VEG	<0.001*** (0.41)	<0.001*** (0.21)		
FSG	1.000 (0.02)	<0.001*** (0.21)	<0.001*** (0.42)	

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

the highest level of heterogeneity, followed by the safety, technological, and economic dimensions (see Table 7 and ESI12†). To overcome the limitations of the K–W test (see Section 2.3 and ESI7†) and establish more robust comparative insights, PLS-MGA is carried out, as reported in Section 6.2–6.5. Crucially,

Table 9 Baseline group: Fornell Larcker results for assessing of discriminant validity

	BLR	FP	HOB	ADPT	PC	PP	SP
BLR	0.729						
FP	−0.107	0.763					
HOB	0.613	−0.130	0.822				
PAP	0.494	−0.262	0.486	0.735			
PSC	−0.140	0.310	−0.135	−0.350	0.877		
PP	0.208	−0.087	0.212	0.458	−0.279	0.781	
SP	0.337	−0.139	0.423	0.491	−0.214	0.283	0.859

Table 10 Baseline group: heterotrait-monotrait results for assessing discriminant validity

	BLR	FP	HOB	ADPT	PSC	PP	SP
BLR							
FP	0.167						
HOB	0.797	0.112					
PAP	0.599	0.254	0.520				
PSC	0.203	0.286	0.175	0.417			
PP	0.251	0.106	0.244	0.478	0.350		
SP	0.425	0.119	0.484	0.528	0.267	0.321	

PLS-MGA supports both parametric and non-parametric tests (see Section 6.3). Critically, whereas the K–W test is performed *via* univariate analysis[126] – relying on post-hoc calculations to calculate *p*-values and effect sizes – PLS-MGA provides a more robust (second-generation) multivariate technique.[322,323]

6.2 Measurement model assessment

Item reliability is supported when indicator loadings exceed a Cronbach Alpha (CA) value of 0.708,[105,111] signifying that the construct explains more than 50% of the variance in an associated indicator.[105] The proposed model is composed of 29 indicators, resulting in total of 116 measurements across all sub-groups. Overall, only 8.6% of indicators ($N = 10$) measured below 0.708 (see ESI13†), but crucially all values were above 0.40 which is acceptable when conducting exploratory research and testing new measurement items.[106,324] As a result, indicators such as PP1 were retained to support content validity,[324] which is a common occurrence when carrying out social science research and developing

Table 8 Baseline group: assessment of reliability, convergent validity, and multicollinearity[a]

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Safety perceptions (SP)	0.911	0.916	0.934	0.738	1.356
Perceived boiler performance (BLR)*	0.703	0.712	0.818	0.532	1.602
Perceived hob performance (HOB)*	0.839	0.841	0.893	0.675	1.602
Technology perceptions (TP)**	0.760	0.760	0.893	0.807[b]	1.254
Financial perceptions (FP)	0.759	0.767	0.802	0.581	1.119
Perceived socio-economic costs (PSC)	0.703	0.724	0.869	0.769[c]	1.208
Production perceptions (PP)	0.841	0.872	0.885	0.610	1.167
Perceived adoption potential (PAP)	0.841	0.854	0.876	0.541	n/a

[a] ** Higher-order construct. * Lower order constructs. [b] Results for validating the higher order construct (TP) are reported in ESI14. [c] Since PSC has two indicators, the AVE is by default larger than 0.50.

Table 11 Assessment of equal distribution of mean values and variances of composites

Group comparison	Equal mean value: Original difference	Permutation mean difference	95% confidence interval	Permutation *p*-value	Equal variances: Original difference	Permutation mean difference	95% confidence interval	Permutation *p*-value	Full measurement variance established
BLG-MEG									
SP	−0.184	0.000	[−0.121; 0.118]	0.001	−0.079	0.004	[−0.154–0.161]	0.342	No
BLR	−0.097	−0.001	[−0.120; 0.114]	**0.116**	−0.043	0.003	[−0.208–0.220]	**0.678**	**Yes**
FP	0.145	0.000	[−0.116; 0.115]	0.014	0.175	0.003	[−0.155–0.170]	0.036	No
HOB	−0.140	0.001	[−0.122; 0.116]	0.022	−0.057	0.002	[−0.201–0.204]	0.560	No
PSC	0.181	0.001	[−0.118; 0.115]	0.002	−0.057	0.000	[−0.166–0.169]	0.521	No
PP	−0.484	0.002	[−0.120; 0.124]	0.000	0.214	−0.002	[−0.178–0.158]	0.017	No
TP	−0.134	0.000	[−0.120; 0.115]	0.027	−0.058	0.002	[−0.214–0.217]	0.598	No
BLG-VEG									
SP	−0.576	−0.001	[−0.132; 0.127]	0.000	−0.186	0.005	[−0.178–0.175]	0.034	No
BLR	−0.394	0.003	[−0.123; 0.136]	0.000	0.013	0.000	[−0.220–0.220]	0.896	No
FP	0.255	−0.003	[−0.136; 0.119]	0.000	0.116	0.006	[−0.192–0.224]	0.258	No
HOB	−0.431	0.002	[−0.125; 0.132]	0.000	−0.074	−0.001	[−0.204–0.218]	0.511	No
PSC	0.103	0.002	[−0.131; 0.128]	0.127	−0.557	0.004	[−0.169–0.182]	0.000	No
PP	−0.868	−0.002	[−0.132; 0.130]	0.000	0.194	0.004	[−0.176–0.174]	0.037	No
TP	0.456	0.002	[−0.123; 0.138]	0.000	−0.071	−0.001	[−0.214–0.237]	0.564	No
BLG-FSG									
SP	−0.118	0.002	[−0.124; 0.126]	**0.067**	0.050	0.001	[−0.179–0.186]	**0.577**	**Yes**
BLR	−0.154	0.000	[−0.134; 0.124]	0.013	0.015	0.000	[−0.210–0.200]	0.886	No
FP	0.216	0.002	[−0.127; 0.129]	0.002	0.080	0.000	[−0.159–0.159]	0.350	No
HOB	−0.107	−0.001	[−0.129; 0.133]	**0.096**	0.045	0.002	[−0.200–0.212]	**0.685**	**Yes**
PSC	−0.084	0.001	[−0.131; 0.126]	**0.197**	−0.137	−0.001	[−0.171–0.168]	**0.119**	**Yes**
PP	−0.059	0.001	[−0.119; 0.129]	**0.382**	0.109	0.003	[−0.173–0.198]	**0.235**	**Yes**
TP	−0.141	−0.001	[−0.124; 0.123]	0.028	0.045	0.002	[−0.209–0.222]	0.664	No
MEG-VEG									
SP	−0.396	−0.002	[−0.138–0.132]	0.000	−0.109	0.002	[−0.186–0.197]	0.257	No
BLR	−0.293	−0.001	[−0.147; 0.135]	0.000	0.056	0.002	[−0.260–0.273]	0.656	No
FP	0.087	−0.001	[−0.141; 0.142]	**0.239**	−0.046	0.002	[−0.196–0.204]	**0.670**	**Yes**
HOB	−0.291	−0.003	[−0.146; 0.132]	0.000	−0.016	0.004	[−0.223–0.237]	0.897	No
PSC	−0.060	−0.001	[−0.137; 0.139]	0.401	−0.504	0.004	[−0.178–0.178]	0.000	No
PP	−0.482	−0.003	[−0.142–0.132]	0.000	0.003	0.004	[−0.174–0.180]	0.978	No
TP	−0.319	−0.003	[−0.138–0.137]	0.000	−0.010	0.004	[−0.252–0.259]	0.934	No
MEG-FSG									
SP	0.069	−0.003	[−0.133; 0.133]	**0.294**	0.129	0.003	[−0.217–0.210]	**0.221**	**Yes**
BLR	−0.057	−0.001	[−0.135; 0.136]	**0.424**	0.056	0.000	[−0.255–0.235]	**0.662**	**Yes**
FP	0.091	−0.005	[−0.148; 0.133]	**0.202**	−0.101	0.001	[−0.180–0.169]	**0.265**	**Yes**
HOB	0.036	0.000	[−0.153; 0.137]	**0.601**	0.102	0.003	[−0.200–0.223]	**0.353**	**Yes**
PSC	−0.258	0.000	[−0.141; 0.140]	**0.001**	−0.079	0.006	[−0.169–0.196]	**0.397**	**Yes**
PP	0.448	0.000	[−0.138; 0.129]	**0.000**	−0.106	0.003	[−0.185–0.195]	**0.294**	**Yes**
TP	−0.003	−0.001	[−0.146; 0.141]	**0.962**	0.102	0.002	[−0.228–0.239]	**0.388**	**Yes**
VEG-FSG									
SP	0.470	0.003	[−0.143; 0.154]	0.000	0.237	0.002	[−0.226–0.206]	0.030	No
BLR	0.245	0.000	[−0.146; 0.158]	0.002	−0.004	0.002	[−0.236–0.240]	0.968	No
FP	0.027	0.000	[−0.147; 0.153]	**0.727**	−0.055	0.002	[−0.219–0.215]	**0.634**	**Yes**
HOB	0.334	0.001	[−0.141; 0.151]	0.000	0.121	0.002	[−0.248–0.219]	0.300	No
PSC	−0.171	0.003	[−0.148; 0.145]	0.028	0.431	−0.003	[−0.179–0.168]	0.000	No
PP	0.849	0.001	[−0.151; 0.145]	0.000	−0.089	0.002	[−0.192–0.203]	0.413	No
TP	0.327	0.001	[−0.147; 0.148]	0.000	0.117	0.003	[−0.260–0.245]	0.349	No

Table 12 Comparative assessment of path coefficients within the structural model for each pairwise comparison[a]

Group comparison	Path coefficients			Statistical test			
BLG–MEG	BLG	MEG	Absolute difference	Parametric *t*-test (equal var.)	Parametric *t*-test (unequal var.)	MGA two-tailed	Permutation *ρ*-value
SP → PAP	0.220	0.316	−0.096	0.075	0.073	0.075	0.087*
BLR → TP	0.477	0.493	−0.016	0.437	0.441	0.439	0.416
HOB → TP	0.633	0.613	0.021	0.394	0.387	0.384	0.351
TP → PAP	0.352	0.217	0.136	0.020	0.019	0.018	0.014**
FP → PAP	−0.118	−0.123	0.004	0.923	0.923	0.916	0.911
PSC → PAP	−0.138	−0.269	0.131	0.009	0.010	0.010	0.012**
PP → PAP	0.265	0.251	0.014	0.779	0.778	0.779	0.798
Group comparison	Path coefficients			Statistical test			
BLG–VEG	BLG	VEG	Absolute difference	Parametric *t*-test (equal var.)	Parametric *t*-test (unequal var.)	MGA two-tailed	Permutation *ρ*-value
SP → PAP	0.220	0.320	−0.099	0.102	0.106	0.105	0.103
BLR → TP	0.477	0.461	0.017	0.425	0.382	0.379	0.403
HOB → TP	0.633	0.629	0.004	0.865	0.855	0.851	0.880
TP → PAP	0.352	0.181	0.171	0.010	0.009	0.010	0.008***
FP → PAP	−0.118	−0.074	−0.045	0.366	0.350	0.350	0.340
PSC → PAP	−0.138	−0.141	0.003	0.957	0.953	0.957	0.952
PP → PAP	0.265	0.377	−0.113	0.047	0.048	0.052	0.027**
Group comparison	Path coefficients			Statistical test			
BLG–FSG	BLG	FSG	Absolute difference	Parametric *t*-test (equal var.)	Parametric *t*-test (unequal var.)	MGA two-tailed	Permutation *ρ*-value
SP → PAP	0.220	0.284	−0.064	0.286	0.301	0.302	0.280
BLR → TP	0.477	0.461	0.017	0.468	0.487	0.485	0.465
HOB → TP	0.633	0.656	−0.022	0.416	0.427	0.425	0.429
TP → PAP	0.352	0.200	0.113	0.029	0.039	0.040	0.021**
FP → PAP	−0.118	−0.131	0.152	0.808	0.818	0.799	0.789
PSC → PAP	−0.138	−0.193	0.054	0.293	0.289	0.290	0.277
PP → PAP	0.265	0.265	0.000	0.995	0.995	0.999	0.995
Group comparison	Path coefficients			Statistical test			
MEG – VEG	MEG	VEG	Absolute difference	Parametric *t*-test (equal var.)	Parametric *t*-test (unequal var.)	MGA two-tailed	Permutation *ρ*-value
SP → PAP	0.316	0.320	−0.004	0.956	0.956	0.960	0.944
BLR → TP	0.493	0.461	0.033	0.149	0.130	0.126	0.137
HOB → TP	0.613	0.629	−0.016	0.534	0.526	0.523	0.536
TP → PAP	0.217	0.181	0.035	0.602	0.605	0.604	0.579
FP → PAP	−0.123	−0.074	−0.049	0.349	0.348	0.341	0.341
PSC → PAP	−0.269	−0.141	−0.128	0.021	0.015	0.015	0.010**
PP → PAP	0.251	0.377	−0.127	0.037	0.038	0.040	0.022**
Group comparison	Path coefficients			Statistical test			
MEG–FSG	MEG	FSG	Absolute difference	Parametric *t*-test (equal var.)	Parametric *t*-test (unequal var.)	MGA two-tailed	Permutation *ρ*-value
SP → PAP	0.316	0.284	0.032	0.624	0.628	0.627	0.603
BLR → TP	0.493	0.461	0.033	0.203	0.207	0.204	0.198
HOB → TP	0.613	0.656	−0.043	0.135	0.141	0.138	0.146
TP → PAP	0.217	0.200	0.016	0.825	0.829	0.827	0.831
FP → PAP	−0.123	−0.131	0.008	0.887	0.889	0.877	0.890
PSC → PAP	−0.269	−0.193	−0.076	0.182	0.179	0.177	0.169
PP → PAP	0.251	0.265	−0.014	0.815	0.816	0.814	0.805

Table 12 (*Contd.*)

Group comparison	Path coefficients			Statistical test			
VEG–FSG	VEG	FSG	Absolute difference	Parametric *t*-test (equal var.)	Parametric *t*-test (unequal var.)	MGA two-tailed	Permutation *ρ*-value
SP → PAP	0.320	0.284	0.035	0.626	0.625	0.627	0.606
BLR → TP	0.461	0.461	0.000	0.996	0.996	0.996	0.998
HOB → TP	0.629	0.656	−0.027	0.374	0.365	0.363	0.374
TP → PAP	0.181	0.200	−0.019	0.820	0.818	0.819	0.831
FP → PAP	−0.074	−0.131	0.057	0.352	0.343	0.336	0.332
PSC → PAP	−0.141	−0.193	0.051	0.340	0.333	0.333	0.287
PP → PAP	0.377	0.265	0.113	0.084	0.084	0.086	0.083*

[a] *** Statistically significant at the 1% level. ** Statistically significant at the 5% level. * Statistically significant at the 10% level.

new theoretical perspectives.[324] This decision was supported since other reliability and validity requirements were fulfilled, as described in the following sub-sections.

6.2.1 Internal consistency reliability. Internal consistency reliability tests the extent to which indicator variables load on their assigned construct (*i.e.* latent variable).[325] The recommended threshold for establishing Composite Reliability (CR) is a value above 0.70,[106] although 0.60 may be permitted when conducting exploratory research.[62] As reported in Table 8, rho_a (ρ_A),‡‡‡‡‡[325] all values except for safety perceptions ($\rho_A = 0.916$) measured between 0.70 and 0.90 for the BLG, thereby satisfying recommended guidelines. All ρ_A values fell between 0.70 and 0.90 for the FSG, whereas two values exceeded 0.90 for the MEG (SP = 0.925; FP = 0.933), while the safety perceptions construct measured 0.931 for the VEG. Critically, all results fell below less stringent upper threshold of 0.95, thereby supporting content validity and suggesting minimal risk of indicator redundancy.[105]

6.2.2 Convergent and discriminant validity. The last stage of the measurement model assessment involves establishing convergent validity and discriminant validity.[326,327] To support convergent validity, the recommended average variance extracted (AVE)§§§§§ for each construct should exceed 0.50, which indicates that, on average, the construct explains more than 50% of the variance of its items.[327] As reported in Table 8, this condition was met in all cases for the BLG and also fulfilled for all remaining sub-groups (see ESI13†).

Discriminant validity establishes whether constructs can be considered empirically distinct from one another,[105] whereby indicator loadings should be highest in relation to the target construct,[62,106] as tested *via* the Fornell Larcker criterion[328] and fulfilled for each sub-group (see Table 9). Henseler and colleagues[326] developed the heterotrait-monotrait (HTMT) ratio of correlations as a more sensitive and robust measure of discriminant validity.[329,330] Discriminant validity was further supported since each construct fell below the more stringent threshold of 0.85 (ref. 326) as documented in Table 10. Additionally, no instances of multicollinearity were observed since all VIF scores measured below the threshold of 3.0.[111]

6.3 Measurement invariance test of composite models

Following the measurement model assessment, the MICOM procedure was employed to validate the scope of comparing sub-groups *via* PLS-MGA.[62–64] Firstly, configural invariance was established by ensuring identical treatment when configuring the STEEP model for each sub-group.[64] Additionally, compositional was verified by ensuring that the composite scores across all sub-groups are perfectly correlated.[130] At the final stage, partial measurement invariance was established for five of the six group comparisons (see Table 11), thereby confirming the validity of evaluating group-specific differences.[64,130] In one case, full measurement invariance was established (between the MEG and FSG), which infers the groups can be considered homogenous and the datasets can be pooled.

Having established the grounds for conducting MGA in PLS-SEM,[64,130] the intended objective could be fulfilled by analysing the potential differences in path coefficients for each pairwise comparison. Results from PLS-MGA indicate different degrees of consumer heterogeneity between five of the six pairwise comparisons, with the MEG and FSG testing non-significant (*i.e.* homogenous) following composite equality, as previously acknowledged and reported for completeness in Tables 11 and 12. In the following summary, results for the permutation ρ-value are reported (see Table 12), as this metric is considered the most robust of the available tests.[128]

Firstly, when comparing the BLG and MEG, two statistically significant differences are observed, namely, for technology perceptions ($\rho = 0.014$) and perceived socio-economic costs ($\rho = 0.012$). Additionally, the result for safety perceptions proved significant at the 10% level ($\rho = 0.087$). Secondly, two constructs have distinct effects on perceived adoption potential when considering the BLG and VEG. Foremost, technology perceptions is statistically significant at the 1% level ($\rho = 0.008$), while production perceptions is significant at the 5% level ($\rho = 0.027$). Additionally, safety perceptions is close to significant at the 10%

‡‡‡‡‡ Formally, the Henseler and Dijkstra rho.[325] ρ_A is the most robust measure of internal consistency, usually reporting a value between CA and Dillon–Goldstein rho_c (ρ_C), which estimate lower and upper bounds.[105]

§§§§§ Calculated as the mean of the squared loadings for all indicators associated with a construct.[327]

Table 13 Results of path analysis and hypothesis testing for consumer sub-groups[a]

Hypothesis	β coefficient	t-Statistic	ρ-Value	f^2	Result
Baseline group					
H1a: SP → (+) PAP	0.220	6.387	<0.001	0.075*	Accepted
H2a: BLR → (+) TP	0.477	37.036	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.633	39.841	<0.001	n/a	Accepted
H2c: TP → (+) PAP	0.352	9.196	<0.001	0.199**	Accepted
H3a: FP → (−) PAP	−0.118	4.055	<0.001	0.025*	Accepted
H4a: PSC → (−) PAP	−0.138	4.431	<0.001	0.032*	Accepted
H5a: PP → (+) PAP	0.265	8.200	<0.001	0.121*	Accepted
Moderately engaged group					
H1a: SP → (+) PAP	0.316	7.769	<0.001	0.177**	Accepted
H2a: BLR → (+) TP	0.493	30.042	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.613	34.459	<0.001	n/a	Accepted
H2c: TP → (+) PAP	0.217	5.037	<0.001	0.088*	Accepted
H3a: FP → (−) PAP	−0.123	3.379	0.001	0.031*	Accepted
H4a: PSC → (−) PAP	−0.269	6.750	<0.001	0.131*	Accepted
H5a: PP → (+) PAP	0.251	6.447	<0.001	0.109*	Accepted
Very engaged group					
H1a: SP → (+) PAP	0.320	6.303	<0.001	0.141*	Accepted
H2a: BLR → (+) TP	0.461	32.897	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.629	34.268	<0.001	n/a	Accepted
H2c: TP → (+) PAP	0.181	3.391	0.001	0.050*	Accepted
H3a: FP → (−) PAP	−0.074	1.944	0.052	0.011	Rejected
H4a: PSC → (−) PAP	−0.141	4.107	<0.001	0.041*	Accepted
H5a: PP → (+) PAP	0.377	8.048	<0.001	0.246**	Accepted
Fuel stressed group					
H1a: SP → (+) PAP	0.284	5.538	<0.001	0.120*	Accepted
H2a: BLR → (+) TP	0.461	23.115	<0.001	n/a	Accepted
H2b: HOB → (+) TP	0.656	28.469	<0.001	n/a	Accepted
H2c: TP → (+) PAP	0.200	3.176	0.002	0.058*	Accepted
H3a: FP → (−) PAP	−0.131	2.772	0.006	0.030*	Accepted
H4a: PSC → (−) PAP	−0.193	4.755	<0.001	0.058*	Accepted
H5a: PP → (+) PAP	0.265	5.825	<0.001	0.114*	Accepted

[a] ** Moderate effect size. * Small effect.

level ($\rho = 0.103$), which is in line with the previous observation between the BLG and MEG. Overall, the data suggests that respondents with higher levels technology and environmental engagement present different hydrogen perceptions when compared against a control group. Thirdly, a statistically significant finding is recorded between the BLG and FSG in relation to technology perceptions ($\rho = 0.021$). Furthermore, perceived socio-economic costs ($\rho = 0.010$) and production preferences ($\rho = 0.022$) present statistically significant differences between the MEG and VEG. Finally, production perceptions are significantly different between the VEG and FSG, albeit at the 10% level ($\rho = 0.083$).

Based on these observations, it can be inferred that four constructs – technology perceptions, perceived socio-economic costs, safety perceptions, and production perceptions – partially explain differences in perceived adoption potential between consumer sub-groups. By contrast, financial perceptions appear to be somewhat homogenous across the sub-samples, while the performance aspects of hydrogen boilers and hobs are perceived similarly across consumer segments. The next stage builds upon these findings by comparing the path coefficients between structural models for each sub-group and discussing the implications of the results.

6.4 Patial least squares multigroup analysis

The bootstrapping procedure (10 000 sub-samples)[121] was applied to statistically examine the proposed hypotheses (see Section 3) for each consumer sub-group (see ESI13†). As reported in Table 13, the model explains perceived adoption potential meaningfully in all cases, albeit with some notable intricacies between sub-groups (see Fig. 11). Supporting the reliability of the proposed model (see Section 6.4.2), in-sample predictive power for each sub-group proved comparable to the full sample ($R^2 = 0.535$): BLG = 0.502; MEG = 0.539; VEG = 0.538; and FSG = 0.478.

For the BLG, all results proved significant at the 0.1% level. For the MEG, six tests returned a ρ-value of <0.001, while the result for financial perceptions was near equivalent ($\rho = 0.001$). In the case of the VEG, similar patterns were detected since

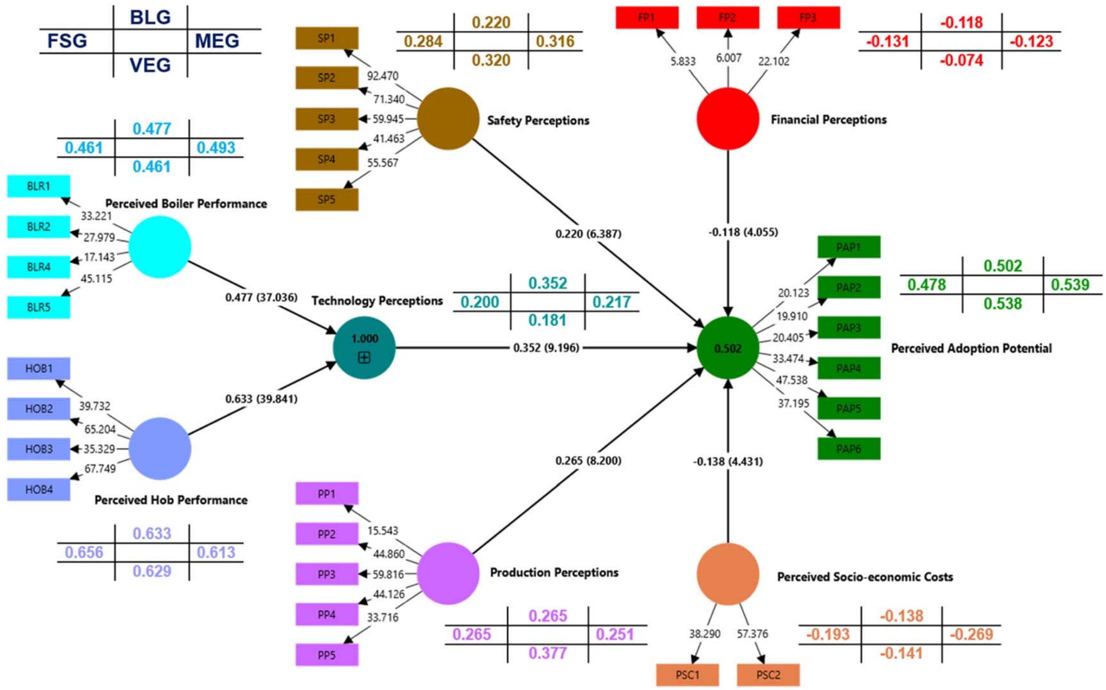

Fig. 11 Structural model path coefficients for consumer sub-groups and R^2 for perceived adoption potential. BLG = Baseline Group; MEG = Moderately technology and environmentally Engaged Group; VEG = Very technology and environmentally Engaged Group; FSG = Fuel Stressed Group.

most results proved significant at the less than 0.1%, while technology perceptions was near equivalent ($\rho = 0.001$). However, one construct, namely, financial perceptions, proved close to significant at the 5% level ($\rho = 0.052$). Consequently, this relationship presents an outlier within the MGA. Lastly, for the FSG, technology perceptions ($\rho = 0.002$) and financial perceptions ($\rho = 0.006$) proved statistically significant at the 1% level, while all other constructs returned a ρ-value of <0.001.

As a result, hypotheses H1a (SP), H2a (BLR), H2b (HOB), H2c (TP), H4a (PSC), and H5a (PP) are supported for each consumer sub-group. Regarding the influence of financial perceptions (FP) on perceived adoption potential, the stated hypothesis (H3a) is fully supported for the BLG, MEG, and FSG, but only partially supported for the VEG. However, H3a is rejected for the VEG in view of comparative findings reported in Table 12, which categorised this result as somewhat of an outlier.

6.4.1 Summary of comparative findings. The results reported in Table 13 enable in-depth comparative analysis regarding the observed differences between sub-groups. Firstly, in terms of safety perceptions (H1a), the effect size is moderate for the MEG ($f^2 = 0.177$), but small across the remaining sub-groups ($f^2 = 0.075$–0.141). Foremost, the positive effect of hydrogen safety is notably smaller for the BLG ($\beta = 0.220$) compared to other sub-groups ($\beta = 0.284$–0.320). As a result, H1b is partially supported in view of group-specific differences between the BLG and MEG, which are significant at the 10% level ($\rho = 0.087$).

Secondly, in terms of technology perceptions (H2c), a notable difference is detected between the BLG and other consumer sub-groups. Although the path coefficients for perceived boiler performance (H2a: $\beta = 0.461$–0.493) and perceived hob performance (H2b: $\beta = 0.613$–0.656) are relatively consistent across all groups, leading to comparable outcomes for each hypothesis ($\rho < 0.001$), this range widens when testing H2c: $\beta = 0.181$–0.352. A moderate effect size is reported for the BLG ($f^2 = 0.199$), whereas all other groups present a small effect for technology perceptions ($f^2 = 0.050$–0.088). Although H2d and H2e are rejected due to conformity regarding perceptions of each hydrogen technology, H2f is fully supported in view of statistically significant differences between the BLG and MEG, and BLG and FSG at the 1% level, in addition to stronger divergence between the BLG and VEG ($\rho = 0.008$).

In respect to financial perceptions (H3a), small effect sizes are reported for all groups ($f^2 = 0.025$–0.031), except the VEG which is non-significant ($\beta = 0.074$; $f^2 = 0.011$). Consequently, at the individual sub-group level, H3a is rejected for the VEG, which is the only hypothesis unsupported across the MGA. While results from the MICOM procedure suggest homogeneity between sub-groups regarding financial perceptions, the subsequent assessment highlights a discrepancy which infers a degree of consumer heterogeneity.

While H3b is rejected due to a lack of group-specific differences, the evaluation of respective path coefficients presents the VEG as an outlier in respect to financial perceptions. As further discussed in Section 6.6, this divergence may be attributed to the influence of socio-demographic variables such as income level and involvement in financial decision-making. For example, in the Chinese context, Lei *et al.*[192] showed that high-income consumers are more likely to have a pro-environmental preference and early adoption potential, whereas lower income

Table 14 Results of predictive power using $PLS_{predict}$

		Root mean square error (RMSE)[a]		Mean absolute error (MAE)[b]	
Items	Q^2 predict	PLS-SEM	Linear model	PL-SEM	Linear model
Baseline group					
PAP1	0.099	0.888	0.889	0.711	0.712
PAP2	0.093	0.910	0.913	0.724	0.731
PAP3	0.111	0.892	0.890	0.708	0.707
PAP4	0.333	1.599	1.641	1.229	1.249
PAP5	0.385	1.649	1.650	1.274	1.269
PAP6	0.401	1.663	1.553	1.292	1.183
Moderately engaged group					
PAP1	0.098	0.913	0.915	0.732	0.726
PAP2	0.108	0.927	0.932	0.750	0.747
PAP3	0.128	0.941	0.949	0.758	0.755
PAP4	0.342	1.557	1.550	1.170	1.183
PAP5	0.421	1.532	1.517	1.189	1.194
PAP6	0.386	1.503	1.482	1.193	1.147
Very engaged group					
PAP1	0.173	0.882	0.889	0.698	0.707
PAP2	0.178	0.923	0.949	0.737	0.767
PAP3	0.171	0.953	0.946	0.766	0.773
PAP4	0.331	1.633	1.656	1.199	1.276
PAP5	0.416	1.607	1.579	1.187	1.201
PAP6	0.280	1.462	1.395	1.160	1.114
Fuel stressed group					
PAP1	0.099	0.911	0.920	0.727	0.729
PAP2	0.155	0.866	0.873	0.688	0.685
PAP3	0.165	0.931	0.953	0.750	0.747
PAP4	0.295	1.688	1.763	1.313	1.352
PAP5	0.299	1.771	1.818	1.373	1.383
PAP6	0.362	1.665	1.686	1.305	1.267

[a] The square root of the average of the squared differences between the predictions and the actual observations. [b] The average absolute difference between the predicted and the actual values.

groups follow a more rational purchasing preference for energy-efficient home appliances.

Regarding perceived socio-economic costs (H4a), while the effect size is small for all sub-groups, the influence of this construct is notably stronger among the MEG ($\beta = 0.269$, $f^2 = 0.131$), whereas other sub-groups are comparatively more homogenous ($\beta = 0.138$–0.193; $f^2 = 0.032$–0.058). H4b is fully supported following group-specific differences between both the BLG and MEG, and BLG and VEG, which proved significant around the 1% level.

Lastly, the positive influence of production perceptions (H5a) on perceived adoption potential is highest among the VEG ($\beta = 0.377$), corresponding to a moderate effect ($f^2 = 0.246$). By contrast, this relationship is highly consistent across the remaining sub-groups ($\beta = 0.251$–0.265), yielding a weak to moderate positive effect on the target outcome ($f^2 = 0.109$–0.121) as captured in Table 12, thereby affirming H5b.

In summary, the PLS-MGA highlights group-specific differences in relation to all constructs within the model, excluding the lower order constructs which leads to rejection of H2d (Perceived Boiler Performance) and H2e (Perceived Hob Performance). The following patterns emerge from the data in regard to perceived adoption potential for hydrogen homes: the positive effect of technology perceptions is highest for the BLG; the negative effect of financial perceptions is least pronounced and non-significant (at the 5% level) for the VEG; the negative effect of perceived socio-economic costs is highest for the MEG; the positive effect of safety perceptions registers strongest for the MEG and least for the BLG; and finally, the positive effect of production perceptions is markedly higher for the VEG (see ESI15†).

6.4.2 In-sample and out-of-sample predictive power. Following the comparative assessment of structural models, in-sample (*i.e.* explanatory) and out-of-sample predictive power[331–333] are evaluated for each sub-group (see Table 14 and ESI16†). Firstly, the coefficient of determination (R^2) reports the level of variance explained by all predictor variables in relation to the final endogenous construct[88,333,334] (*i.e.* perceived adoption potential). A general rule of thumb suggests R^2 values of 0.25, 0.50, and 0.75 reflect small, medium, and large effect sizes.[335] However, as documented in social science studies, R^2 is influenced by the nature of the subject matter, with large effect sizes seldom reported.[336,337]

In-sample predictive power closely converged across the sub-groups, ranging from $R^2 = 0.478$ for the FSG, to $R^2 = 0.539$ for the MEG (mean $R^2 = 0.514$; R^2 for the full sample = 0.535).

Table 15 CVPAT benchmark and results for predictive ability test

Perceived adoption potential	PLS loss	IA loss	Average loss difference	*t*-Value	*p*-Value
PLS-SEM vs. Indicator average (IA)					
BLG	1.743	2.594	−0.852	10.344	<0.001
MEG	1.601	2.386	−0.785	9.234	<0.001
VEG	1.654	2.408	−0.754	6.973	<0.001
FSG	1.876	2.617	−0.750	7.819	<0.001
PLS-SEM *vs.* Linear model (LM)					
BLG	1.743	1.708	0.035	1.475	0.141
MEG	1.601	1.585	0.016	0.519	0.604
VEG	1.654	1.628	0.026	0.501	0.617
FSG	1.867	1.962	−0.095	2.402	0.017

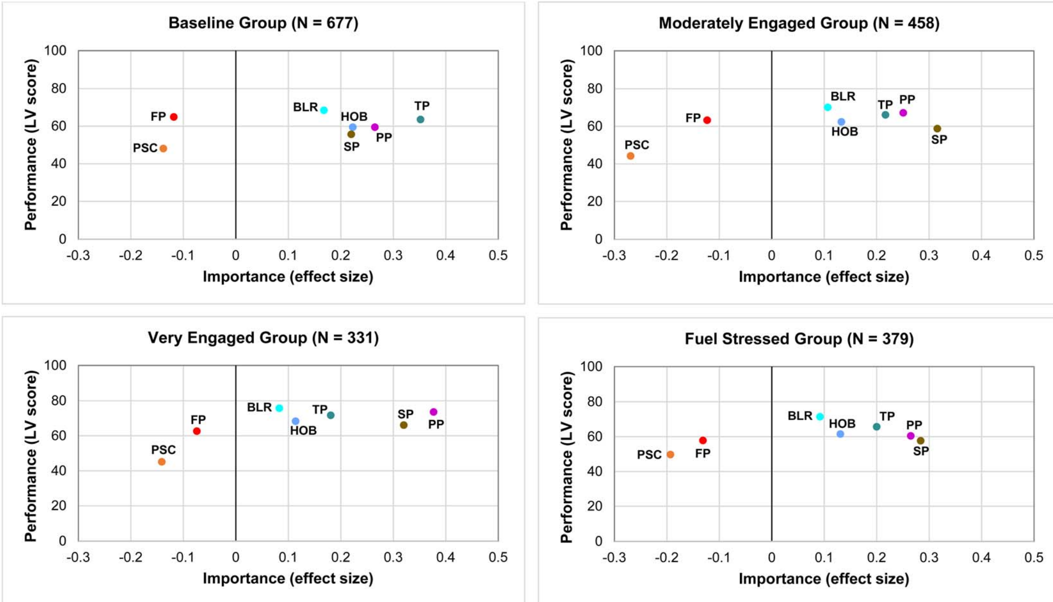

Fig. 12 Importance-performance map analysis of perceived adoption potential of hydrogen homes across consumer sub-groups. Turquoise = Perceived Boiler Performance (BLR); Blue = Perceived Hob Performance (HOB); Green = Technology Perceptions (TP); Red = Financial Perceptions (FP); Orange = Perceived Socio-economic Costs (PSC); Brown = Safety Perceptions (SP); Purple = Production Perceptions (PP).

Table 16 Results summary for necessary condition analysis

Consumer sub-group	Effect size (permutation value) per construct: Safety perceptions (H1c)	Technology perceptions (H2g)	Production perceptions (H5c)	Range by sub-group (SD)
BLG	0.182 (<0.001)	0.212 (<0.001)	0.158 (0.003)	0.184 (0.027)
MEG	0.149 (0.003)	0.150 (0.018)	0.159 (<0.001)	0.153 (0.006)
VEG	0.149 (<0.001)	0.163 (<0.001)	0.259 (<0.001)	0.190 (0.060)
FSG	0.192 (0.001)	0.274 (<0.001)	0.268 (0.001)	0.245 (0.046)
Mean (SD)	0.168 (0.022)	0.200 (0.056)	0.211 (0.061)	

Consequently, the STEEP model demonstrates moderate in-sample predictive power, explaining around 50% of the variance in perceived adoption potential across consumer sub-groups.

An initial measure of out-of-sample predictive power is provided by calculating the Stone-Geisser's Q^2 value for the endogenous construct.[338,339] Q^2 results approximated or exceeded 0.50, indicating moderate to strong predictive power for each sub-group:[105] BLG = 0.490; MEG = 0.520; VEG = 0.516; FSG = 0.451. To further assess out-of-sample predictive power,[340] this analysis draws on the $\text{PLS}_{\text{predict}}$ tool developed by Shmueli *et al.*[341] and the cross-validated predictive ability test (CVPAT) espoused by Liengaard and colleauges.[342]

For the BLG, four of the six indicators outperformed the naïve linear model (LM).[105] For the MEG and VEG, this held true for three indicators, while all six indicators outperformed the LM benchmark for the FSG. Accordingly, results from $\text{PLS}_{\text{predict}}$ suggest that STEEP framework has high out-of-sample predictive power when tested on the FSG, while other sub-samples exhibit moderate predictive power.[105] Additionally, out-of-sample predictive power proved higher for each sub-group as compared to the full sample (see ESI16†).

Results from the CVPAT corroborate this finding, since the average difference between the PLS-SEM model and the indicator average (IA) proved negative, and significantly below zero.[342] However, as reported in Table 15, the model lacks strong predictive accuracy for the BLG, MEG, and VEG, since it fails to outperform the more conservative linear model (LM) prediction benchmark.[343] Nevertheless, results for the FSG reinforce the relatively strong predictive capabilities of the STEEP framework for examining the antecedents of domestic hydrogen adoption potential ($t = 2.402$, $\rho = 0.017$).

6.5 Synthesis of findings for importance-performance map analysis

To extract additional value from PLS-MGA, IMPA is conducted for each sub-group to identify priority zones for strengthening adoption prospects for hydrogen homes (see ESI17†). The output from the IMPA helps visualise the differences between sub-groups (see Fig. 12), which can help guide policy makers and key stakeholders when taking strategic decisions on residential decarbonisation.

Table 17 Bottleneck tables showing percentile results for enabling perceived adoption potential

Perceived adoption potential	Safety perceptions	Technology perceptions	Production perceptions
Baseline group (BLG)			
0	0	0	0
10	0.148	0	0
20	0.739	0	0.148
30	0.886	0	0.148
40	0.886	0.886	0.148
50	0.886	0.886	0.148
60	2.806	0.886	0.148
70	2.806	14.771	0.148
80	6.352	14.771	13.442
90	52.290	46.381	33.235
100	77.696	93.058	77.400
Moderately technology and environmentally engaged group (MEG)			
0	0	0	0
10	0.218	0	0.218
20	0.218	0	0.218
30	0.218	0	0.218
40	0.218	0	0.873
50	0.218	0.655	0.873
60	0.437	0.873	3.057
70	2.838	0.873	3.057
80	3.493	2.838	3.057
90	8.297	32.751	7.424
100	47.380	80.786	62.445
Very technology and environmentally engaged group (VEG)			
0	0	0	0
10	0	0.302	0
20	0	0.302	0
30	0.302	0.302	0.604
40	0.302	0.302	0.604
50	0.604	0.302	0.604
60	0.604	0.906	0.604
70	3.927	0.906	0.604
80	3.927	0.906	3.625
90	6.949	47.734	26.284
100	43.807	86.103	71.299
Fuel stressed group			
0	0	0	0
10	0	0	0.264
20	0.792	0	0.264
30	0.792	0	0.264
40	0.792	0	0.264
50	0.792	2.375	0.264
60	2.902	2.639	0.264
70	2.902	8.443	0.792
80	3.430	29.024	8.971
90	14.2480	57.520	78.1
100	85.488	63.588	95.778

The results suggest that higher levels of technology and environmental engagement correspond to a stronger influence of production perceptions on perceived adoption potential, thereby elevating the importance of the environmental dimension. After production perceptions, safety perceptions is the next most influential positive factor among respondents composing the VEG, however, these dynamics are reversed among respondents in the MEG. In comparative terms, financial perceptions appear to be less relevant to the MEG compared to other constructs, which calls for further interrogation and validation in follow-up studies, for example, by testing moderating effects related to socio-demographic variables (see Section 7.2).

Bridging the gap between the VEG and MEG, the effect size of production perceptions and safety perceptions is near equal among respondents who are non-engaged and fuel stressed. However, technology perceptions emerges as the most influential aspect for respondents who are non-engaged and non-fuel stressed, as captured *via* the BLG. Financial perceptions and perceived socio-economic costs have a similar effect on perceived adoption potential for baseline respondents. However, more resources should be allocated towards mitigating socio-economic concerns, since this construct had the lowest latent variable (LV) index value (*i.e.* worst performance) in the model (LV = 48.056). Interestingly, perceived boiler performance has the highest LV index value in each IMPA, which implies there is less scope to improve consumer perceptions of hydrogen heating compared to hydrogen cooking.

6.6 Multigroup necessary condition analysis

6.6.1 Insights from bottleneck tables and permutation test results. The MGA is completed by complementing results from PLS-SEM with necessary condition analysis, thereby integrating insights from both a sufficiency and necessity perspective within the same study.[67,73] Following the guidelines presented in Section 2.4, the ceiling envelopment free disposal hull (CE-FDH) is applied to evaluate the necessary conditions for enabling perceived adoption potential across each sub-group (see ESI8†). In conjunction, bottleneck tables are produced to verify the level of each positive predictor (*i.e.* SP, TP, and PP) that is required to achieve a specific level of the target outcome. In addition to evaluating necessary conditions in degree,[65] the permutation test for NCA is carried out (see Table 16).[136]

Several patterns emerge from the data as further evidenced in Table 17 (see ESI18†). Firstly, all necessary condition hypotheses are supported, with consistent findings of medium effect sizes (*i.e.* $0.1 \leq d < 0.3$) across the sample. Nevertheless, variance is detected across the three critical success factors, as well as between sub-groups. On average, production perceptions has the largest effect size (H1c: $d = 0.211$), followed by technology perceptions (H2g: $d = 0.200$), and safety perceptions (H5c: $d = 0.168$). Notably, safety perceptions is a more homogenous factor from a necessity perspective (SD = 0.022) than technology perceptions (SD = 0.056), and production perceptions (SD = 0.061).

Each critical success factor has a near equivalent effect size among respondents in the MEG ($d = 0.153$, SD = 0.006), which is notably smaller compared to other sub-groups. By contrast, the mean value for the FSG is closer to a large effect size ($d = 0.245$, SD = 0.046), with technology perceptions registering the strongest influence across the sample ($d = 0.274$). Additionally, the results affirm that the environmental perspective associated with production perceptions is the most critical success factor for enabling perceived adoption potential among the VEG ($d =$

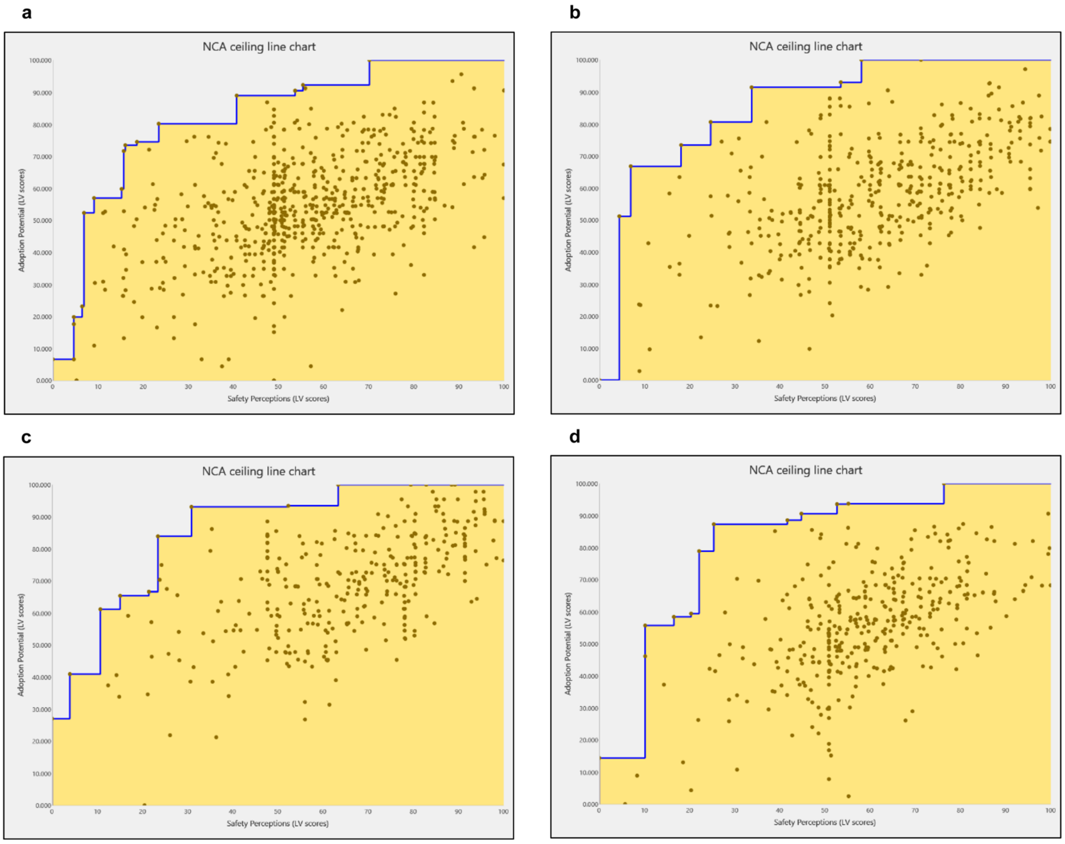

Fig. 13 Necessary condition analysis ceiling line charts (CE-FDH) for safety perceptions as a predictor of perceived adoption potential. (a) Baseline Group (BLG): $d = 0.182$; (b) Moderately technology and environmentally Engaged Group (MEG): $d = 0.149$; (c) Very technology and environmentally Engaged Group (VEG): $d = 0.149$; (d) Fuel Stressed Group (FSG): $d = 0.192$.

0.259), which is also the segment with the highest level of variance across necessary conditions ($d = 0.190$, SD = 0.060).

The reported results are visualised in the form of NC-MGA ceiling line charts for each construct, as illustrated in Fig. 13–15. Accordingly, it emerges that the empty space in the upper left area of the scatter plot is significantly higher in specific instances, such as technology perceptions and production perceptions for the FSG (see Fig. 14d and 15d), as well as production perceptions for the VEG (see Fig. 15c). Moreover, the bottleneck results show that a minimum level of each critical factor is needed to enable 40%, 50%, 30%, and 50% perceived adoption potential for the BLG, MEG, VEG, and FSG, respectively. In practical terms, this corresponds to the following set of parallel conditions regarding consumer perceptions: hydrogen must be rated safer than natural gas; hydrogen home appliances must be appraised as technologically superior to natural gas appliances; and hydrogen production perceptions associated with the twin-track approach must be positive.

Table 18 summarises the results obtained through PLS-NC-MGA to merge findings from each technique. It follows that safety, technology, and production perceptions – reflecting the safety, technological, and environmental perspectives of the STEEP Framework – are both 'should-have' and 'must-have' factors for enabling perceived adoption potential. However, the consistency of significant findings from both a sufficiency and necessity perspective may otherwise mislead policy makers and key stakeholders into assuming the best approach is to seek boosting all three areas indiscriminately.

While such an approach should invariably raise overall adoption prospects for hydrogen homes, a more strategically sound approach lies within factoring consumer heterogeneity into the equation. An active and measured response to emerging patterns of heterogenous household preferences, as opposed to a uniform response, holds significant potential for mitigating the risk of devising ineffective, one-size-fits-all strategies for residential decarbonisation. To support this pathway, Section 6.6.2 illuminates the findings through presentation of 'bottleneck charts', while Section 6.6.3 completes the investigation by integrating combined importance-performance map analysis (cIMPA) as part of the multigroup research approach.

6.6.2 Insights from bottleneck charts. Bottleneck charts provide a more direct means for comparing necessary conditions within a multigroup research design (see ESI20†), which can help streamline data-rich insights to decision-makers.[344] Since failure rates are relatively low at the 70% level across constructs (BLG = 5.91%; MEG = 2.26%; VEG = 1.81%; FSG = 4.05%; $M = 3.51\%$), the analysis is conducted at the 80% level, in addition to the 90% and maximum (100%) adoption potential levels. The following cut-offs are applied to guide the

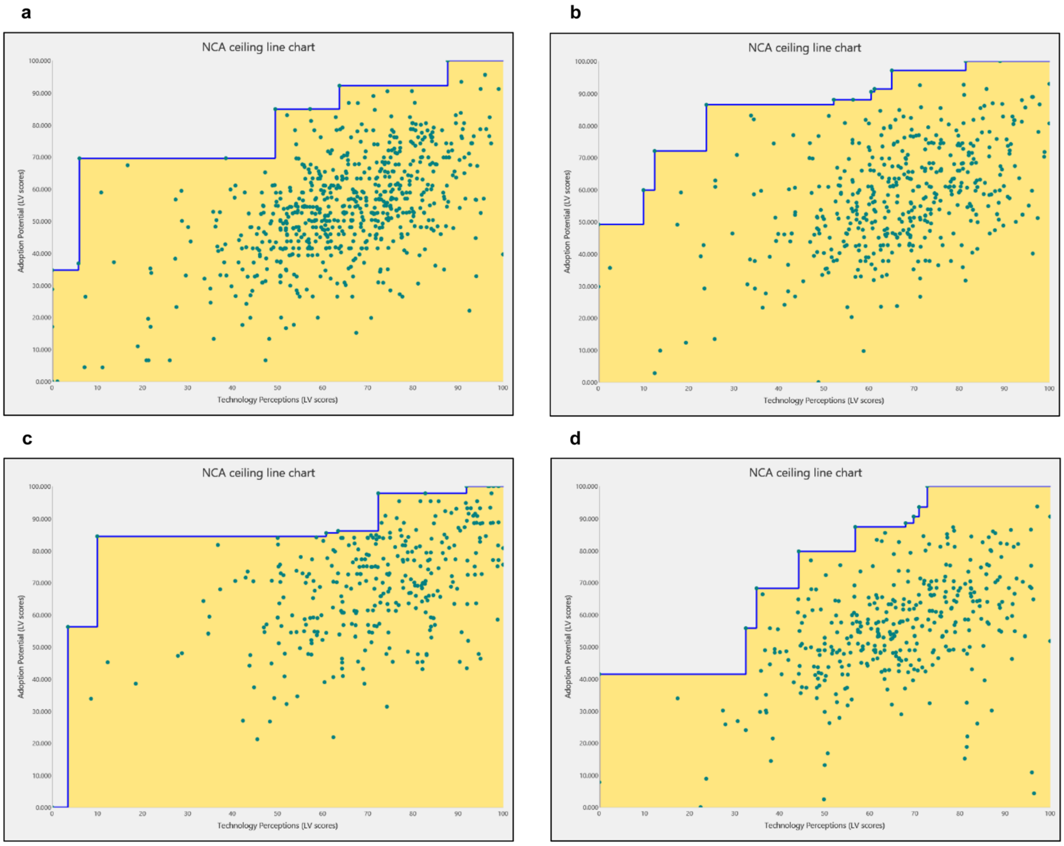

Fig. 14 Necessary condition analysis ceiling line charts (CE-FDH) for technology perceptions as a predictor of perceived adoption potential. (a) Baseline Group (BLG): $d = 0.212$; (b) Moderately technology and environmentally Engaged Group (MEG): $d = 0.150$; (c) Very technology and environmentally Engaged Group (VEG): $d = 0.163$; (d) Fuel Stressed Group (FSG): $d = 0.274$.

analysis by considering the respective failure rate (FR): minor bottleneck = FR < 10%; small bottleneck = 10% ≤ FR < 25%; moderate bottleneck = 25% ≤ FR < 50%; significant bottleneck = 50% ≤ FR < 75%; substantial bottleneck = FR ≥ 75%.

It emerges more clearly that each segment presents its own unique dynamics, although the MEG and VEG are relatively similar from a necessity perspective when considering all available pairwise comparisons. Perceived adoption potential for the BLG is constrained by a lack of positive safety perceptions, which creates a significant bottleneck at the 90% level (FR = 52.90%). At the 100% level, safety perceptions creates a moderate bottleneck for the MEG (FR = 47.38%) and VEG (FR = 43.81%), and a substantial bottleneck for the BLG (FR = 77.70%) and the FSG (FR = 85.49%), as depicted in Fig. 16.

By comparison, technology perceptions presents a moderate bottleneck for the FSG at the 80% level (FR = 29.02%), which is also the case for the BLG, MEG, and VEG at the 90% level of perceived adoption potential. However, at 90%, technology perceptions corresponds to a significant bottleneck for the FSG (FR = 57.52%). Interestingly, at the maximum level of perceived adoption potential, technology perceptions remains a significant bottleneck for the FSG (FR = 63.59%) but now presents a substantial bottleneck for all remaining sub-groups (see Fig. 17).

Finally, regarding the environmental perspective, production perceptions presents a small bottleneck at the 80% level for the BLG (FR = 13.44%) but increases to a moderate bottleneck at the 90% level (FR = 33.24%), before becoming a substantial bottleneck at the 100% level (FR = 77.4%). For the MEG, production perceptions remains a minor bottleneck at both the 80% and 90% levels of perceived adoption potential but increases to a significant bottleneck at 100% (FR = 62.45%). Patterns deviate for the VEG since production perceptions creates a moderate bottleneck at the 90% level (FR = 26.28%) and a significant bottleneck when maximising the target outcome (FR = 71.30%). Lastly, the FSG presents a notable outlier when considering perceived adoption potential at the 90% level, since the bottleneck result is substantial (FR = 78.1%), while 95.8% of respondents failed to meet the requisite support level for enabling maximum adoption potential, as illustrated Fig. 18.

Results from the NCA bottleneck tables (see Table 17) reinforce the extent to which engagement in technology and the environment increases the adoption prospects hydrogen homes. Across the three necessary conditions – SP, TP, and PP – 11.5% and 13.8% of respondents fail to meet the required level for enabling 80% perceived adoption potential among the BLG and FSG, compared to 3.1% and 2.8% for the MEG and VEG.

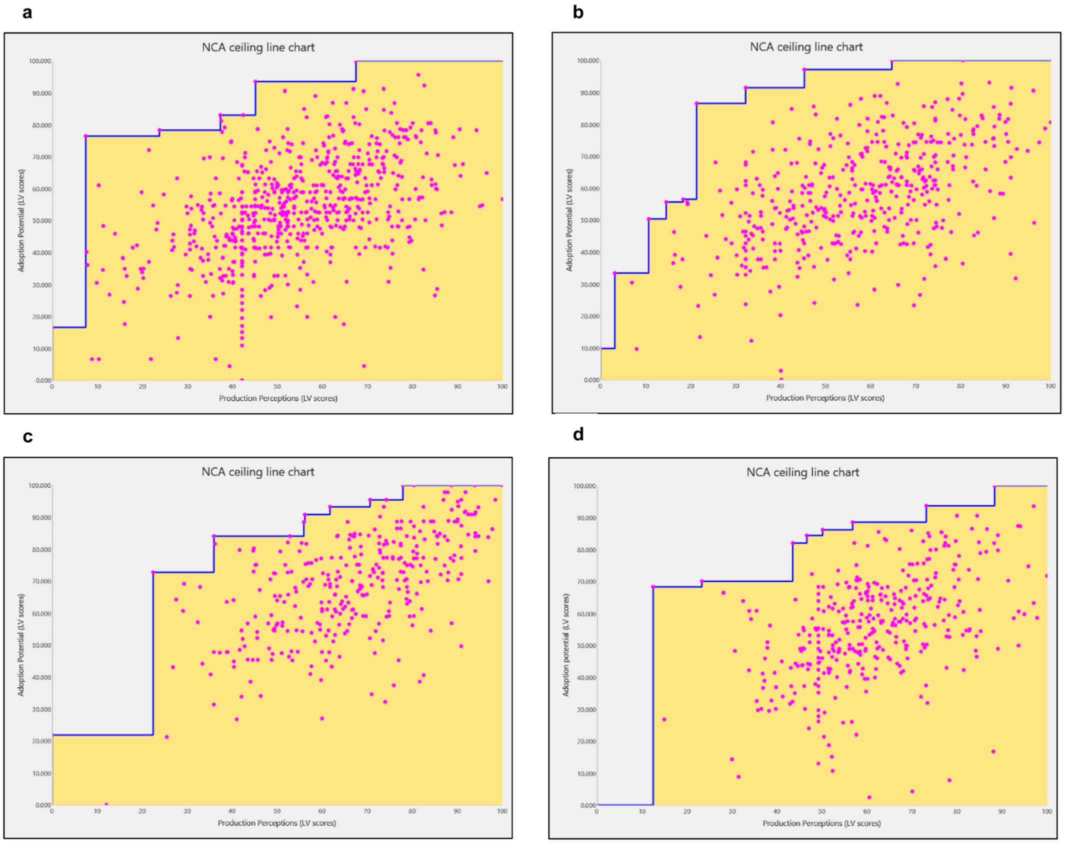

Fig. 15 Necessary condition analysis ceiling line charts (CE-FDH) for production perceptions as a predictor of perceived adoption potential. (a) Baseline Group (BLG): $d = 0.158$; (b) Moderately technology and environmentally Engaged Group (MEG): $d = 0.159$; (c) Very technology and environmentally Engaged Group (VEG): $d = 0.259$; (d) Fuel Stressed Group (FSG): $d = 0.268$.

However, at the 90% level, perceived adoption potential also becomes significantly constrained for both the MEG and VEG ($M = 21.57\%$), as reflected in Fig. 16–19. As a result, a starting point is to target an initial increase from 80% to 90% perceived adoption potential through segment-specific strategies, whereas maximising the examined target outcome presents a less feasible or plausible target.[345]

Fig. 19 provides a comparative analysis across constructs and consumer sub-groups for the 90% and 100% levels of perceived adoption potential, thereby confirming that the environmental

Table 18 Results summary for partial least squares-necessary condition-multigroup analysis

Consumer sub-group	PLS-SEM results: path coefficient; *p*-value)	NCA results: *d*; *p*-value	Significant determinant and a necessary condition?
Construct: safety perceptions			
BLG	H1a: 0.220; <0.001	H1c: 0.182; <0.001	Supported
MEG	H1a: 0.316; <0.001	H1c: 0.149; 0.003	Supported
VEG	H1a: 0.320; <0.001	H1c: 0.149; <0.001	Supported
FSG	H1a: 0.284; <0.001	H1c: 0.192; 0.001	Supported
Construct: technology perceptions			
BLG	H2c: 0.352; <0.001	H2g: 0.212; <0.001	Supported
MEG	H2c: 0.217; <0.001	H2g: 0.150; 0.018	Supported
VEG	H2c: 0.181; 0.001	H2g: 0.163; <0.001	Supported
FSG	H2c: 0.200; 0.002	H2g: 0.274; <0.001	Supported
Construct: production perceptions			
BLG	H5a: 0.265; <0.001	H5c: 0.158; 0.003	Supported
MEG	H5a: 0.251; <0.001	H5c: 0.159; <0.001	Supported
VEG	H5a: 0.377; <0.001	H5c: 0.259; <0.001	Supported
FSG	H5a: 0.265; <0.001	H5c: 0.268; 0.001	Supported

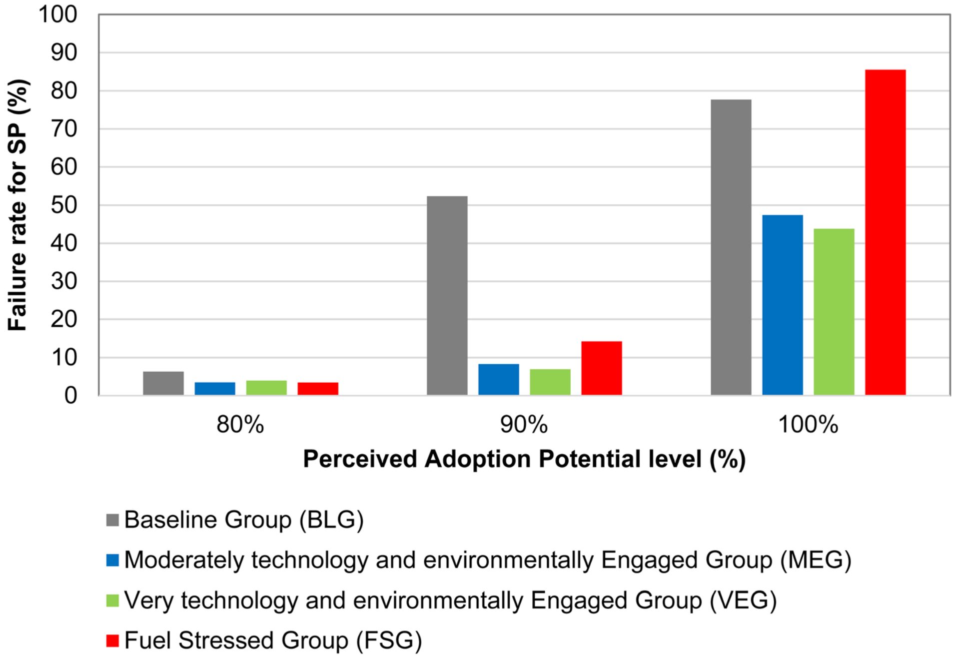

Fig. 16 Bottleneck chart for safety perceptions.

perspective is the most significant bottleneck for securing support for hydrogen homes among fuel stressed consumers, while the technological perspective presents the main constraint among consumers belonging to the BLG. Conversely, the safety perspective is, on average, a less influential constraint on perceived adoption potential across both levels, in addition to the 80% level (see Table 19). Furthermore, Table 19 shows that technology perceptions is the critical success factor with the lowest degree of inter-group variance.

6.6.3 Combined importance-performance map analysis. From a sufficiency perspective (*i.e.* PLS-MGA), the MEG and FSG present highly consistent results (see Table 11), which translates to similar dynamics within the importance performance map (see Fig. 12). From a necessity perspective, more fine-grained patterns emerge which also distinguish the MEG and FSG, as reported in Section 6.6. Fig. 20 leverages data from PLS-MGA (see Table 13 and Fig. 11) and MG-NCA (see Table 17 and ESI19†) to integrate combined importance-performance map

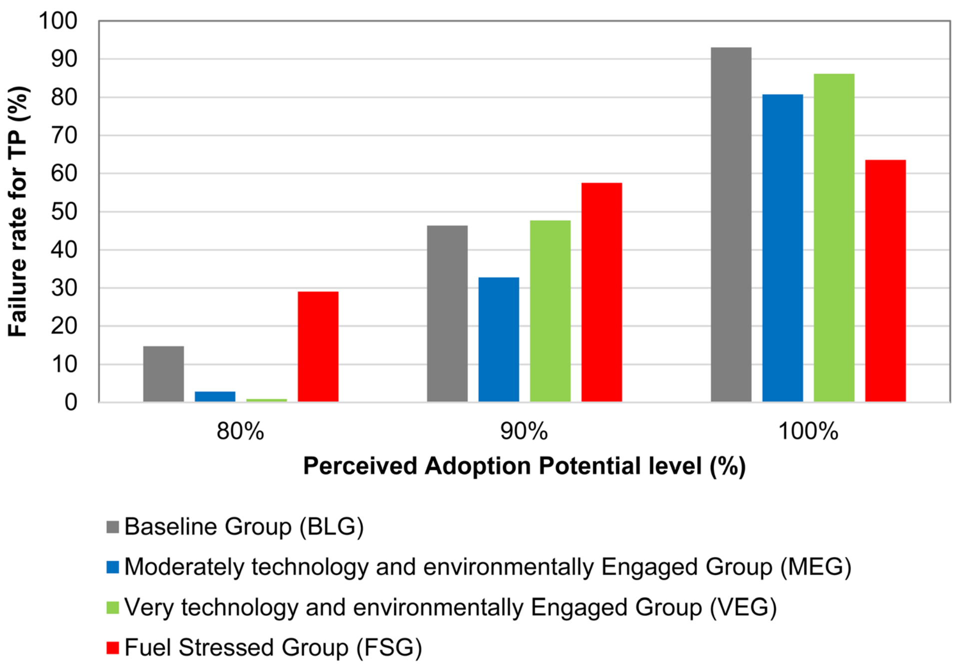

Fig. 17 Bottleneck chart for technology perceptions.

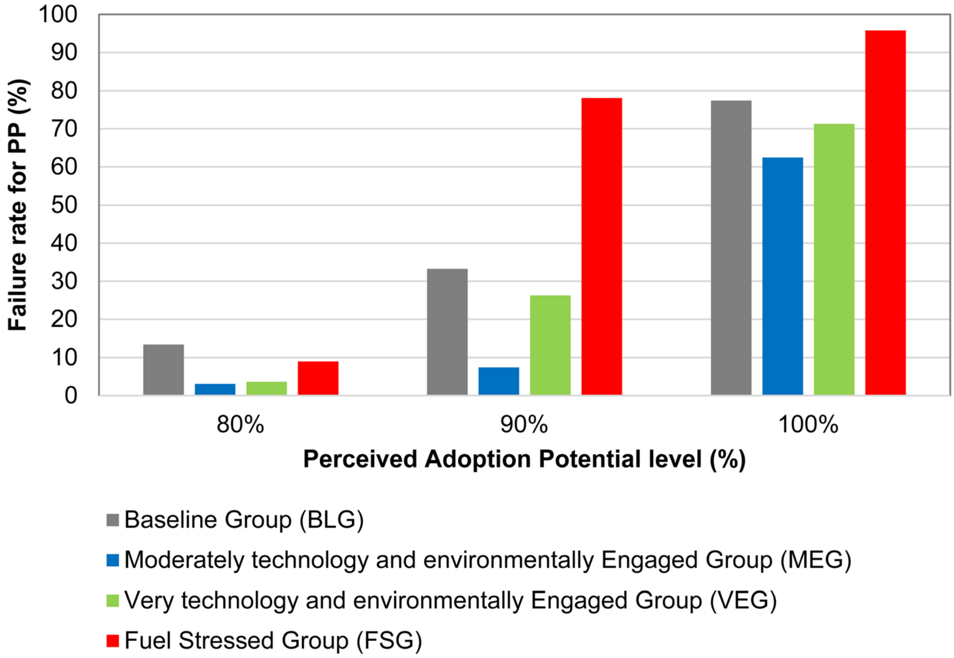

Fig. 18 Bottleneck chart for production perceptions.

analysis (cIMPA)[72] within a multigroup research design for the first time. The analysis focuses on the suggested benchmark of enabling 90% perceived adoption potential.

The results reinforce the prevailing sense of heterogeneous preferences for living in a hydrogen home, as reflected by examining perceived adoption potential among four distinct consumer sub-groups. Consistent with prior results, the largest divergence is observed between the BLG and VEG. Whereas technology perceptions must be improved to enable 90% of the target outcome among consumers belonging to the BLG, the priority for securing support among the VEG rests with securing more positive perceptions of hydrogen production. Furthermore, while safety perceptions is less of a strategic priority than production (and technology) perceptions for consumers in the BLG, safety still presents a substantial bottleneck, while the opposite holds true for the VEG. However, for the MEG and FSG,

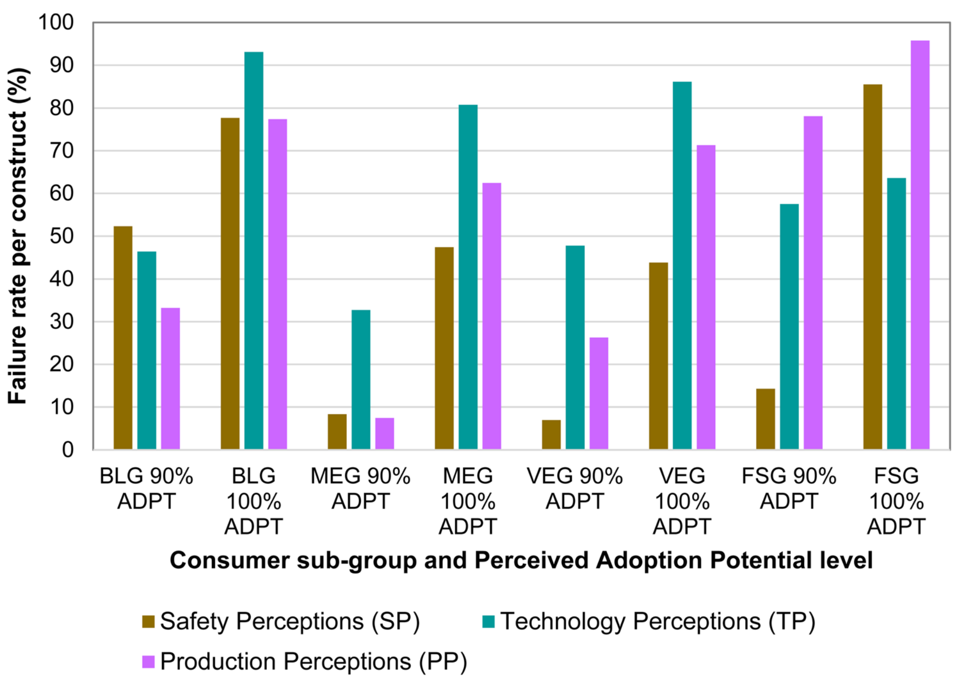

Fig. 19 Bottleneck chart for 90% and 100% perceived adoption potential across consumer sub-groups.

Table 19 Summary of bottleneck results for critical success factors of domestic hydrogen adoption potential

Perceived adoption potential level (%)	Safety perceptions: mean failure rate (SD)	Technology perceptions: mean failure rate (SD)	Production perceptions: mean failure rate (SD)
80	4.30 (1.39)	11.88 (12.97)	7.27 (3.26)
90	20.45 (21.46)	46.10 (10.19)	36.26 (36.19)
100	63.59 (21.08)	80.88 (12.58)	76.73 (17.08)

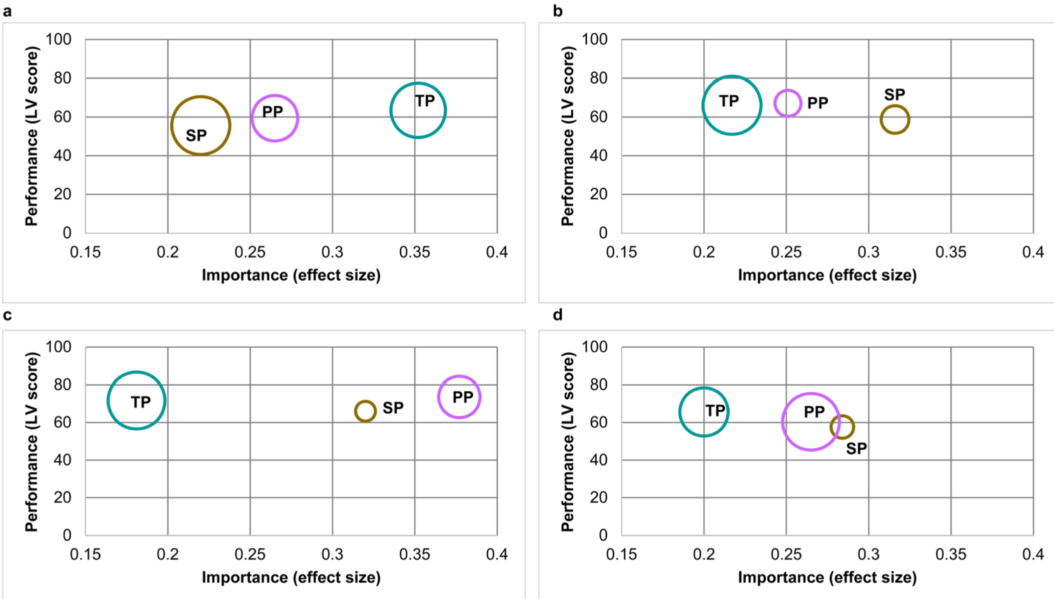

Fig. 20 Combined importance-performance map analysis for enabling 90% adoption potential. (a) Baseline Group (BLG); (b) Moderately technology and environmentally Engaged Group (MEG); (c) Very technology and environmentally Engaged Group (VEG); (d) Fuel Stressed Group (FSG). SP = Safety Perceptions (Brown); TP = Technology Perceptions (Teal); PP = Production Perceptions (Purple).

a mix of different dynamics are observed which further substantiate the need for segment-specific considerations.

It emerges that safety and environmental perspectives present a similar constraint among the MEG, however, there is more strategic value in targeting an improvement in safety, as previously illustrated in Fig. 12. However, an additional insight from the cIMPA is that an improved perception of hydrogen production is more critical for securing a higher level of perceived adoption potential among fuel stressed respondents as compared to the MEG. Thus, while the two groups converged following the MICOM procedure as validated *via* PLS-MGA (see Section 6), NC-MGA reveals more fine-grained insights regarding the presence of consumer heterogeneity.

Compared to the results visualised in Fig. 12, the cIMPA adds significant analytical value by incorporating bottleneck dynamics into the matrix. Key takeaways include showing that technology perceptions presents a similar-sized constraint across all sub-groups but varies in terms of importance while converging in terms of performance. Additionally, while the foremost strategic priority for enabling 90% perceived adoption potential among the VEG rests with improving production perceptions, it also emerges that the environmental perspective is of critical interest to households facing high levels of fuel stress.

7 Discussion

7.1 Practical implications

The analysis suggests that the foremost near-term priority for increasing perceived adoption potential across the general population may lie with strengthening technology perceptions of domestic hydrogen, while production perceptions and to a lesser degree, safety perceptions will also raise adoption prospects. However, Fig. 8 highlights that consumers are unconvinced that the notion of a hydrogen home presents a direct benefit over individual technologies for heating and cooking (*i.e.* boilers and hobs).

This observation is consistent with results reported by Lozano *et al.*[58] in the Australian context, which suggested equivalence between hydrogen for cooking and space heating purposes ($M = 3.60$), but a marginal preference for hot water heating ($M = 3.71$), as measured on a five-point Likert scale. Alternatively, data from online focus groups conducted in the UK ($N = 58$) suggested consumers have a "prevailing tendency" to support the proposition of a hydrogen home over individual technology pathways.[52] The discrepancy likely reflects differences in the characteristics of quantitative and qualitative research methods.[346–348] Conceivably, online survey respondents take a largely objective comparative assessment when evaluating the three metrics. By contrast, focus group respondents may transmit higher levels of subjectivity based on interactions with others,[349,350] and learning through conversation and information provision,[351,352] which seemingly boosted positivity towards hydrogen homes.[52] In reflection, it becomes a clear imperative to ascertain if there is an underlying consumer preference for experiencing a dual technology transition compared to a single pathway which should prioritise hydrogen heating over hydrogen cooking.[68]

In terms of negative predictors, concerns associated with energy insecurity and fuel poverty appear more influential than financial perceptions across the sample. Nevertheless, it should be noted that this relationship is less evident for the BLG, which may be partially attributed to comparatively lower levels of awareness in respect to energy and environmental justice.[47] The moderate influence of financial perceptions may reflect the specificity of acceptance dynamics when appliances are still being tested and yet to be commercialised. Furthermore, the online survey framed the adoption decision for 'before 2030', which may have indirectly reduced attention attributed towards potential financial risks.

Notably, research on rooftop solar PV adoption in Texas has emphasised how financial perceptions (*i.e.* perceived affordability) becomes a more significant factor as consumers progress through the innovation-decision process,[353] which may entail five distinct stages: knowledge → persuasion → decision → implementation → confirmation.[239] Studies on a range of energy technology use cases support the notion that consumers attribute greater importance to financial factors when the adoption decision is imminent, as opposed to hypothetical.[48,249,354]

It follows that during the formative stage of the transition, seeking to strengthen public perceptions of financial costs may be somewhat premature and fail to translate into a shift towards optimism and positivity on the 'hydrogen acceptance matrix', which includes pessimism, scepticism, and cautiousness at the negative end.[83] However, should the safety and environmental case for domestic hydrogen be established, financial costs may likely emerge as the foremost factor in predicting adoption potential and market acceptance.[38] Nevertheless, the announced 'price promise' made by the boiler industry's leading manufacturers (Worcester Bosch, Vaillant, Baxi, and Ideal) must be fulfilled to pre-empt grounds for significant consumer backlash,[355] while a corresponding 'price pledge' on energy bills would be strongly welcomed by UK households given the entrenched challenge of economic instability.[80]

As technology and environmental engagement levels increase and reach a high level, production perceptions and safety perceptions become focal points for strengthening perceived adoption potential, while the technological dimension related to hydrogen appliances is less pronounced. The observed pattern also holds partially true when technology and environmental engagement levels are moderate and under conditions of fuel stress. Safety perceptions appear marginally more important than production perceptions for both the MEG and FSG, while technology perceptions remains the least critical success factor. However, there is more scope for improving perceived adoption potential among fuel stressed consumers by allocating resources towards mitigating socio-economic concerns, which aligns to the disproportionate livelihood pressures facing this demographic.[261] Despite this imperative, when evaluated against other factors, the FSG nevertheless places least weight on the micro-economic dimension associated with the purchasing and running costs of hydrogen appliances. Based on the results, it can be conjectured that citizens facing fuel stress pressures perceive switching to a hydrogen home as a potential mechanism for alleviating safety concerns and improving the environment, which is consistent with prior research.[43,52]

The divergence between sub-groups highlights the scope for increasing social acceptance and associated adoption potential by communicating the prospective performance advantages of hydrogen technologies (*i.e.* boilers and hobs) to the wider population, while targeting information on environmental and safety benefits to other consumer segments. These measures should be prioritised during the formative phase of the transition to establish the requisite level of consumer acceptance to trial and potentially deploy hydrogen homes at scale.

Overall, the findings suggest that non-economic constructs such as safety and technology perceptions[23,39] are potentially more influential during the formative phase of technology diffusion, which has also proved the case for battery electric vehicles.[356] As argued by Bull,[357] market choices often involve a trade-off between several heterogeneous factors such as functionality, performance, and price, with consumers being more likely to concentrate on salient characteristics (*i.e.* efficiency performance) as opposed to unpredictable factors such as future energy costs.

Currently, social acceptance is mainly at stake for hydrogen homes[38] ahead of consumer decision-making and prospective adoption,[48,249,353,354] should a scaling up be greenlighted by the government in the upcoming years.[18] It emerges that any remaining prospects for implementing hydrogen village trials in the UK[18,30] may hinge firmly on communicating the potential for economic, social, and environmental benefits at the community level,[120,292,296] as widely acknowledged in the energy acceptance literature.[358] The evidence suggests that consolidating community acceptance is a prerequisite to enabling household acceptance, which would correspond to the subsequent adoption of hydrogen homes appliances (*i.e.* market acceptance) following local trials.

Identifying and aiming to better understand differences between consumer segments should become a stronger focal point of climate change research,[40,57,359] ahead of policy decisions on the technology portfolio for residential decarbonisation.[18,19] Through a deeper comprehension of the emerging 'contours of consumer heterogeneity',[47] key actors and stakeholders can fine-tune their public engagement strategies to strengthen the enabling conditions for deploying hydrogen homes. A low-hanging fruit for the DESNZ and similar agencies or research bodies it to embed information on self-perceived levels of technology and environmental engagement, and consumer innovativeness (*i.e.* adoption category) when tracking public attitudes towards (hydrogen) energy technologies.[257,282,360]

Table 20 Target interventions for increasing the perceived adoption potential of hydrogen homes

Target intervention	Target outcome(s)	Supporting literature
• Scale-up renewable community projects and local stakeholder engagement	• Improves social trust to support local and regional prospects for converting parts of the gas grid to hydrogen	Ref. 51, 83, 163, 379 and 380
• Support the market deployment of smart home technologies through policy and market mechanisms	• Strengthens prospects for hydrogen adoption via higher levels of consumer innovativeness	Ref. 58, 83 and 381
• Increase climate change and environmental awareness in the context of the built environment through information campaigns	• Increases the feasibility of accelerating residential decarbonisation via environmental engagement	Ref. 58, 83, 242 and 382–384
• Improve energy and hydrogen literacy through targeted measures to inform and engage consumers (*e.g.* when issuing energy bills or updates about energy supply)	• Supports the enabling conditions for deploying hydrogen homes through familiarity and awareness	Ref. 43, 48, 120, 230, 252, 262, 299, 379 and 385
• Communicate the perceived benefits, as well as the costs and risks of the domestic hydrogen transition	• Pre-empts social resistance and mistrust, while strengthening prospects for adoption potential *via* economic, social, and environmental drivers	Ref. 80, 120, 252, 385 and 386
• Target smaller demonstration projects with clear time-horizons and contingency plans, which can sustain public support	• Increases the trialability and observability of hydrogen homes, while mitigating the risk of a negative social representation	Ref. 230, 299, 386 and 387
• Scale up the use of clean hydrogen in industry and leverage potential cross-sectoral synergies	• Legitimises the social license to operate for hydrogen-fuelled communities, which may support a more positive social representation	Ref. 79, 163, 308, 363, 379, 385 and 387
• Consolidate the safety case for converting the gas grid to hydrogen and switching parts of the housing stock to hydrogen-fuelled appliances	• Counteracts the fear factor sometimes associated with hydrogen and builds public confidence in the hydrogen transition and advent of hydrogen homes	Ref. 23, 52, 230, 252 and 385
• Prioritise hydrogen heating over hydrogen cooking	• Mitigates the potential for adverse technology lock-in and derisks pathways which may be socially contested or rejected	Ref. 23, 68 and 79
• Couple segment-specific strategies to spatially-explicit decarbonisation pathways	• Minimises the risk of a mismatch between failing to secure social acceptance and techno-economic feasibility in different jurisdictions	Ref. 36, 47, 230, 363, 364, 369, 379 and 386

Critically, stakeholder symbiosis – with designated and dynamic roles for institutional actors, the energy sector, financial institutions, non-governmental organisations, research institutions, intermediaries, consumers, and other entities – is a critical component of developing national hydrogen economies,[79,361,362] which may include a spatially-explicit role for hydrogen homes in certain jurisdictions.[38,363,364] Similarly, when examining the potential for trialling hydrogen heating in UK communities, Snodin *et al.*[230] highlighted the need for extensive stakeholder mapping, collaborative processes, and consumer segmentation exercises.

In response, Table 20 summarises a series of target interventions to strengthen the preconditions for domestic hydrogen adoption. Overall, this study further motivates the need to integrate spatially-explicit and segment-specific strategies to support the clean energy transition. This dual approach holds significant potential for better navigating the complexities of energy system transformation.[365,366] Accounting for heterogeneity across the two P's – Place and People – can help strengthen potential synergies between techno-economically feasible and socially acceptable decarbonisation pathways.[79,367,368]

In the UK context, this translates into taking a co-ordinated system-wide approach; committed to achieving demand reduction, while scaling up electrification *via* heat pumps and heat networks, alongside harnessing potential opportunities for supplying hydrogen to parts of the housing stock.[19,369] The immediate priority lies with supporting nationwide energy-efficiency schemes,[37,370] especially across fuel poor regions;[371,372] recognising that a net-zero energy future calls for reconceptualising the role of energy efficiency and demand reduction.[373] Secondly, heat pump penetration rates across northern European countries[374] suggest that the UK can overcome barriers to achieve large-scale heat and power decarbonisation through electrification.[13,367] Thirdly, the role of heat networks[375,376] and hydrogen[32,34] in decarbonising the housing stock should be consolidated as early as possible, while also accounting for potential synergies between power-to-hydrogen and heat networks.[377,378]

7.2 Accounting for contextual sources of consumer heterogeneity

Recent failure to secure community acceptance for hydrogen village trials may be partly attributed to a mix of system-level factors and context-specific dynamics;[41,82] including the distribution of fuel stressed households, and relative prevalence of technology and environmentally engaged consumers within locations such as Whitby and Redcar. Crucially, candidate towns for hydrogen homes across the North of England may differ according to historical and cultural heritage, in addition to their socio-economic configuration.[388–390] While a mix of observable and unobservable factors may explain patterns of consumer heterogeneity, a logical starting point it to engage with variables that are tangible and better understood in the technology acceptance literature such as age, gender, and income.[179,183,391]

Consumer heterogeneity may stem from variation in certain socio-demographic variables between sub-groups (see ESI3†), which could potentially moderate the relationship between examined constructs and perceived adoption potential. Moderation occurs when the effect on an exogenous construct on an endogenous construct is not constant but depends on the values of a third construct (*i.e.* the moderating variable).[392–394] Such relationships should be thoroughly examined to advance theoretical knowledge.[126,392]

Notably, the VEG had the largest representation of outright property owners compared to the sample average (+10.2%), whereas mortgage owners were under-represented compared to other sub-groups. This composition may have translated to a more financially secure group with comparatively lower economic concerns at the household level. Support for this notion is directly observed when examining distributions for annual income brackets. The VEG had the lowest representation of respondents with an income below £23 500 (−9.7%), alongside over-representation for the highest income bracket of £62 500+ (+11.2%). Such discrepancies are likely to have mitigated concerns related to financial concerns and may have influenced other predictors such as perceived socio-economic costs. Given that high-socio-economic status consumers have a central role to play in accelerating the diffusion of clean energy technologies,[395] the effect of income disparities should be analysed more directly in future studies.

Regarding perceived socio-economic costs, negativity or concern was attributed foremost to the MEG, which appears somewhat counterintuitive. One possible source of divergence may originate from the interaction between location and area type, which corresponded to an over-representation of respondents from rural parts of Wales and the Southwest of England for the MEG. Policy studies suggest this demographic group is highly susceptible to fuel poverty risks;[396,397] especially among Welsh households where around 17% of rural households are classified as fuel poor compared to 13% for urban areas.[398] Furthermore, the MEG had a lower representation of urban respondents compared to the sample average (−3.9%), whereas the VEG was over-represented (+6.8%).

Additionally, it should be noted that the VEG was over-represented by respondents from the Southeast and London (+8.1%), whereas over-representation within the FSG corresponded to respondents from the North of England and Scotland (+7.9%). However, in the case of the FSG, to an extent, the higher representation was intentionally targeted to make the group more nationally representative of fuel poverty patterns. This divergence feeds into potential group-specific differences which may be linked to location and reflective of the North–South divide.[198,399]

While housing tenure, location, and area type appear to be relevant socio-structural variables, age and gender may also prove important socio-demographic variables, alongside income. Crucially, global-level, cross-country analysis suggests that the mean age of a population holds strong explanatory power for explaining attitudes towards different climate intervention technologies.[400] In the Japanese context, Long *et al.*[401] found that age has a significant (negative) effect on ability to adopt solar PV and low emission vehicles, which is partially attributed to the loss of household income associated with reaching retirement age.

In terms of age, respondents within the VEG were both the youngest (−3.8%) and the oldest (+5.7%). By contrast, the FSG was significantly under-represented by respondents aged 55+ (−7.4%). It is feasible that an increase in age contributes towards negative financial perceptions, as older households may contend with more liabilities and feel risk averse to technology change. Notably, Lozano *et al.*[58] found that older individuals were less likely to support domestic hydrogen in the Australian context. Moreover, the UK population is ageing due to improvements in life expectancy and declining fertility rates,[402,403] which may amplify barriers to adopting clean energy technologies among the older population, as predicted in Japan.[401]

Interestingly, an early study on hydrogen acceptance conducted in the Netherlands showed older age groups held the strongest perception of hydrogen as unsafe,[213] however, subsequent studies are yet to validate this finding. It is also plausible that the partially significant difference between the MEG and BLG for safety perceptions ($p = 0.075$) stems from under-representation of older respondents within the FSG. Future studies can explore whether differences in age are likely to amplify or weaken the positive effect of safety perceptions on perceived adoption potential.

While age may moderate several relationships within the model, gender differences could also help explain some of the observed patterns. For example, in the German context, middle-aged men with technical professions residing in rural or suburban multi-person households are more inclined to invest in electric vehicles (EVs) than other potential adopter groups.[359] Foremost, female respondents were over-represented within the BLG (+7.1%). Other less pronounced differences also defined the distribution of the MEG and VEG, while the FSG was close to nationally representative in terms of gender. Foremost, gender may be an important explanatory factor of technology perceptions, as suggested in previous studies on different energy technologies[404,405] including hydrogen,[58,406]

In the context of EVs, environmentally concerned citizens and innovative consumers in the Netherlands proved more likely to have a stronger adoption intention,[191] which also proved the case in this study. Energy acceptance findings in the Dutch context may prove especially relevant to the UK domestic hydrogen transition, in view of similar contextual conditions and motivations in seeking to decarbonise the residential sector.[407–409]

Table 21 Breakdown of results for categorical filtering results across consumer sub-groups

	Consumer sub-group			
Categorical filter	BLG	MEG	VEG	FSG
Interest and engagement level in environmental issues	2.46	3.52	4.16	2.50
Knowledge and awareness of renewable energy technologies	2.14	3.22	4.19	2.42
Consumer innovativeness	2.61	3.43	4.59	2.94
Total	7.20	10.18	12.94	7.86

Notably, environmental benefits proved the most the significant predictor of consumer heterogeneity when examining qualitative response patterns to this survey.[47] Despite other areas of mixed alignment between results, the PLS-MGA fully validates the notion that perceived environmental benefits (a proxy of production perceptions or environmental attitude) is the most heterogeneous factor of domestic hydrogen acceptance. As a result, findings form this dataset deviate from previous exploratory research, which suggested the twin-track strategy, in its totality, may garner strongest support from fuel stressed respondents.[43]

At a finer level, the small-sample study ($N = 58$) identified technology and renewable energy engaged respondents to be supportive, whereas environmentally engaged citizens were critical of blue hydrogen and had least support for the twin-track approach.[43] However, this study suggests that parallel engagement in renewable technology and environmental issues enhances the positive effect of production perceptions on perceived adoption potential for hydrogen homes. This would imply that environmental concerns associated with a blue hydrogen production pathway are potentially insufficient to override wider support for the energy transition, and by proxy, the deployment of low-carbon hydrogen heating and cooking appliances.

Statistical support for this argument has been provided by Gordon *et al.*[47] in finding the effect of environmental engagement on domestic hydrogen adoption potential ($\beta = 0.287$) to be weaker than the effect of knowledge and awareness of renewable energy technologies ($\beta = 0.308$), and moreover, consumer innovativeness (*i.e.* interest in being an early adopter of new energy technologies: $\beta = 0.324$). A closer inspection of the filtering results reported in Fig. 2 lends potential support for the observed patterns. For all sub-groups, except the MEG, consumer innovativeness levels were higher compared to interest and engagement level in environmental issues, as well knowledge and awareness of renewable energy technologies.

As reported in Table 21, the difference was most pronounced in the case of the VEG and FSG, but also notably higher for the BLG, whereas consumer innovativeness ranked second for the MEG. It is also noteworthy that the FSG presented a higher overall score than the BLG, wherein minimal divergence was observed regarding environmental engagement levels (difference = 0.04). The larger discrepancy between technology engagement levels for the FSG and BLG may further explain underlying patterns of consumer heterogeneity observed within the data, alongside the non-significant result between the MEG and FSG in PLS-MGA. Future research should engage with these dynamics by demarcating between a very technology and a very environmentally engaged group to validate these observations.

In summary, it may be reasoned that controlling for a range of moderating variables[183] such as age, gender, income, and location may influence the dynamics of consumer heterogeneity observed within this study, whereby some relationships may be amplified, while others are weakened. For example, being older may increase financial concerns, while higher annual income may reduce socio-economic concerns. A case in point is the potential economic benefits of EVs remaining more accessible to consumers with a higher socio-economic status.[359]

In response, subsequent studies should conduct moderation analysis and simple slope analysis in PLS-SEM[126,410,411] to examine the potential (moderating) effects of a range of categorical and continuous variables.[126] Critically, testing for moderating effects should have a firm theoretical basis and follow specific guidelines,[126] which can be established and applied in follow-up research to distil further insights on consumer heterogeneity in the context of adoption capacity for hydrogen homes.

8 Conclusion

Drawing on modelling techniques such as PLS-MGA,[74] business researchers have increasingly factored heterogeneity into their studies on consumer acceptance,[334,412] as reflected by the dominance of multigroup analyses in management journals.[64] However, as reviewed in Section 3, there has been limited uptake of MGA among energy acceptance scholars[192] (see Fig. 4).

To date, most multigroup studies tend to constrain their focus to just two groups; even in instances where comparing more groups makes theoretical and empirical sense.[64] Such tendencies stifle research progress towards uncovering critical insights on consumer heterogeneity. Given potential implications for future energy pathways[413,414] and emissions reduction,[415] reversing this trend is especially important in the context of emerging low-carbon technologies[416] such as domestic hydrogen.[48,417] Factoring consumer heterogeneity into behavioural research is especially important during the pre-deployment stage of the technological cycle, where the feasibility of early adoption and potential growth dynamics should be systematically assessed.[41,204,418]

This study makes a substantial contribution to the emerging literature on hydrogen acceptance[252,253] and contributes to the discourse on energy transitions[419,420] by presenting an advanced

MGA, which is applied to the context of hydrogen homes in the UK. By triangulating insights on the should-have and must-have factors of perceived adoption potential *via* IMPA and cIMPA, the findings enrich scholarly understanding on hydrogen futures. In parallel, the research reflects an incremental methodological contribution; enabling scholars to explore the merits of PLS-NC-MGA and readily replicate or adapt the steps presented in Fig. 3 (see Section 2.5). Foremost, new analytical insights are derived by differentiating between three levels of technology and environmental engagement – very engaged, moderately engaged, and non-engaged – while explicitly accounting for fuel stress in the segmentation approach (see Table 2).

While previous studies have taken a mostly binary approach by comparing the effects of innovation category,[58] or gender and political party preferences,[59] on hydrogen acceptance, this study is the first to present a multi-dimensional focus on consumer perceptions and preferences, while shifting the focus towards perceived adoption potential. This lens is critical for advancing insights on the parameters of market acceptance,[52,80] alongside other dimensions such as community acceptance,[38] which is a necessary step for bolstering the growth potential of the hydrogen economy.[53]

The results of this analysis resonate with the call from Lei *et al.*[192] for "common but differentiated household mitigation policies" to support the implementation of energy-saving policies in the urban China, while Long and colleagues[401] further highlight that climate change technologies will have differentiated adoption rates among segments of the Japanese housing stock. In the case of hydrogen homes, results from the intergroup comparison underline the need for segment-specific engagement strategies to strengthen adoption prospects for hydrogen homes across the UK population.

Synthesising the results from the PLS-MG-NCA (see Fig. 11, 19 and 20), this study highlights several critical insights which should be validated in subsequent studies. Future research can overcome certain limitations within this study (see Section 6.6) by securing a more nationally representative sample at the subgroup level, which would allow for thorough examination of moderation effects. Subsequent multigroup approaches should aim to demarcate between technology and environmental engagement by filtering these categories within the research design. Adopting this approach will open new research avenues for comparing fuel stressed respondents who are engaged and non-engaged with technology and the environment. Conducting such a comparison may help reveal more nuanced findings regarding priority areas for enhancing hydrogen acceptance and adoption prospects.

This study motivates the need to sample fuel poor respondents, as opposed to citizens experiencing high levels of fuel stress, as a means of validating the findings and seeking a stricter energy justice lens within the research design.[17,51,261] Critically, the current costs of decarbonisation policies fall disproportionality on low-income households,[421] which exacerbates the prevalence of fuel poverty and energy vulnerability.[261] Another option is to examine the influence of involvement in financial decision-making when choosing between household heating and cooking technologies (see ESI3†).

Other research angles can also be explored in future studies such as comparing consumers from the devolved nations of the UK,[198] or applying a sub-national multigroup approach to explore regional acceptance dynamics.[301] Advancing insights at the national level is an important stepping-stone towards conducting cross-national comparative analyses.[422] Furthermore, researchers should seek to extend the evidence base on the hydrogen economy by evaluating consumer attitudes towards different hydrogen energy technologies and alternative production pathways.[59,302,310] Recent efforts to establish a longitudinal evidence base on hydrogen perceptions should be enhanced,[59,302] while also recognising that both cross-sectional and longitudinal designs offer distinct advantages for testing explanatory mechanisms.[41,423] Future studies on residential heat decarbonisation should also be attuned to a potential seasonality effect, which may imply that perceptions elicited during autumn and winter are distinct compared to spring and summer.

A cross-country MGA examining public perceptions of the hydrogen economy would support recent landmark studies conducted by Andre *et al.*[424] and Baum and colleagues.[400] In parallel, it is critical to examine public perceptions of different residential decarbonisation pathways at the national level[20,249] by systematically comparing public perceptions of hydrogen boilers and heat pumps. Critically, future studies should further unpack the dynamics of technology perceptions in view of perceived performance, which may be achieved by introducing additional measurement items. For example, specific items related to perceptions of performance and controllability for different types of cooking (*e.g.* boiling and simmering, grilling, wok stir-frying *etc.*) should be explored in different contexts including the global south.[425,426]

As net-zero policy making continues to evolve in countries such as the UK, energy researchers can support decision-making processes by exploring novel ways to model the adoption potential of emerging technologies such as domestic hydrogen. Critically, follow-up work should test the robustness of operationalising new constructs integrating aspects of behavioural acceptance (*i.e.* willingness to adopt) and community acceptance (*i.e.* perceived economic, social, and environmental benefits) to bridge the gap between social acceptance and adoption intention. This approach would enable a more comprehensive assessment of whether findings from this study are generalisable to other countries, wherein energy systems, policies, and cultures may somewhat align (*e.g.* the Netherlands) or diverge significantly (*e.g.* Japan).

Alongside a consumer-oriented focus,[68] the perceptions of other stakeholders such as industry and experts should be thoroughly examined to support policy prescriptions on different sectors of the hydrogen economy.[161,165,362,427] Furthermore, UK policy makers have somewhat divergent perceptions of UK heat decarbonisation,[3] which may be more pronounced following recent developments around hydrogen homes and warrants assessment.

Foremost, the presented research offers critical lessons for future trials and demonstration projects, which could see setbacks encountered in Whitby and Redcar overturned by the delivery of the East Coast Hydrogen Project,[428] alongside similar hubs in the UK[161] and internationally.[379,429] Recent history underscores the importance of social acceptance,[430,431] especially at the community-level wherein individual attitudes coalesce.[38] In response, this study demonstrates the efficacy of leveraging advanced MGA to improve the behavioural realism of energy transitions research, while supporting the notion of common but differentiated consumer engagement strategies. Through a hybrid focus on segments of the UK population, the evidence base lays the groundwork for advancing the use of PLS-NC-MGA, as a key mechanism for guiding policy making and managerial decisions on social aspects of the hydrogen economy. As the scope of data analysis methods continues to grow, insights from multigroup research designs can firmly support comprehensive consumer engagement strategies for accelerating residential decarbonisation.

Data availability

https://doi.org/10.17862/cranfield.rd.24517966.v1.

Author contributions

Joel A. Gordon: conceptualization, investigation, data curation, data analysis, visualization, theoretical framework, writing – original draft, writing – review & editing. Nazmiye Balta-Ozkan: conceptualization, funding acquisition, supervision. Anwar Haq: theoretical framework, writing – review & editing. Seyed Ali Nabavi: conceptualization, funding acquisition, supervision.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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