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Exploring the contours of consumer heterogeneity: Towards a typology of domestic hydrogen acceptance

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ABSTRACT

Hydrogen energy technologies are anticipated to play a fundamental role in securing a decarbonised energy future. While the deployment of low-carbon hydrogen energy systems remains nascent and is subject to a range of techno-economic constraints, potential scalability will also hinge on social acceptance. In response, this study draws on extensive national survey data to derive a comprehensive typology of domestic acceptance, which reflects multiple factors influencing consumer attitudes towards low-carbon hydrogen heating and cooking appliances. The proposed typology is developed through rigorous coding of over 1000 qualitative statements, leading to 12 core acceptance factors composed of a mix of positive, neutral, and negative sub-factors. The study finds that eight primary sub-factors account for close to 60 % of identified codes, with knowledge deficit (negative), environmental benefits (positive), and financial risks (negative) ranking highest. Critically, these three sub-factors are also the most statistically significant predictors of consumer heterogeneity. At the sub-group level, the analysis shows that engagement with renewable energy technology and climate change is associated with stronger perceptions of environmental benefits and lower financial concerns. By contrast, perceived financial risks and concerns over energy injustice constrain acceptance levels among fuel stressed respondents. Through mixed-methods analysis, the study transmits the value of advancing acceptance typologies as a critical mechanism for enacting a 'just' hydrogen economy. The analysis supports developing strategic measures which account for consumer heterogeneity to better support socially acceptable pathways for residential decarbonisation.

1. Introduction

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

In December 2017, Japan emerged as the first country to release a national hydrogen strategy [15]. In the intervening years, several countries such as Australia [7], Chile [16], and European Union (EU) Member States [17] have followed in Japan's footsteps by developing official strategies, as outlined in Supplementary note 1 (see SN1). Of foremost relevance to this study, the United Kingdom (UK) government published its hydrogen strategy in August 2021 [19] ahead of COP26 in Glasgow [18]. Notably, the strategy sets out a vision for enabling production, distribution, storage, and use of hydrogen to support economic opportunities across the country's industrial heartlands [19].

The UK government foresees a potential role for hydrogen in residential decarbonisation [19], alongside heat pumps, district heating [20,21], and other electric-based technologies such as induction hobs [22,23]. Importantly, prospects for 'hydrogen homes' – composed of low-carbon hydrogen boilers and hobs [24,25] – entail a definitive

Abbreviations: BLG, Baseline Group; EU, European Union; FSG, Fuel Stressed Group; MEG, Moderately Engaged Group; RETs, renewable energy technologies; VEG, Very Engaged Group; US, United States; UK, United Kingdom.

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spatial component [26,27] which may present synergies with industrial decarbonisation via hydrogen [28]. Reflecting these spatial dynamics, the government's strategy envisions the launch of hydrogen village trials [29–31] in proximity to industrial clusters [32–34], ahead of a strategic decision on the role of domestic hydrogen in 2026 [19].

A prominent example of recent hydrogen research, development, and deployment activities is the HyDeploy project, which Isaac [35] describes as "the first stepping-stone for setting technical, operation and regulatory precedents of the hydrogen vector."[1] The third and final phase of the project (HyDeploy3) focuses on enabling government policy on domestic hydrogen [36]. Supporting related social science research on domestic hydrogen acceptance [37–40], part of the HyDeploy evidence base includes a comparative assessment of consumer perceptions of blended hydrogen in Keele (West Midlands) and Winlaton (Northeast England) [41].

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

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

Against this backdrop, this study has three connected aims: (1) to identify the salient core factors of domestic hydrogen acceptance; (2) to determine the salient sub-factors of domestic hydrogen acceptance; and (3), to establish which sub-factors predict consumer heterogeneity. Pursuing the final line of inquiry is crucial since Bharadwaj and colleagues [78] have shown that the effects of information provision on different consumer sub-groups are heterogeneous, while Gordon et al. [23] reported divergent consumer preferences for cooking and heating technologies in the UK. Moreover, subsequent research demonstrates heterogeneous preferences for living in a hydrogen home among different parts of the UK housing stock [79]. Through methodological and empirical contributions, the main objective of the research is to advance an initial typology of domestic hydrogen acceptance, which can be refined or extended in subsequent research to support public engagement in the domestic hydrogen transition, while accounting for the influence of consumer heterogeneity.

To achieve its objective, this study draws on written responses (N = 1064) to an open-ended online survey question, wherein participant communicated a wide range of perceptions reflecting different acceptance factors. Specifically, several iterations of hybrid deductive-inductive coding were performed to derive the final set of acceptance sub-factors (N = 48), which map to 12 core factors (see Section 4). Contributing to the growing evidence base on energy acceptance, the proposed typology demarcates critical parameters for supporting a socially acceptable transition to hydrogen homes and the wider hydrogen economy. This marks a novel contribution to the literature as the first study to derive an energy acceptance typology based on qualitative evidence sourced from a dataset of over 1000 individual responses. By contrast, previous studies have largely relied on secondary data from literature review to identify the salient factors of hydrogen acceptance [76,80].

The remainder of the paper is structured as follows. Section 2 reviews the literature on hydrogen acceptance, while Section 3 reports the research design and mixed-methods approach. Next, Section 4 reports the results which includes analysing the predictors of consumer heterogeneity in Section 4.6. The key findings are discussed in Section 5, while Section 6 concludes the study by proposing policy recommendations and outlining a future research agenda.

2. Literature review

2.1. Conceptualising domestic hydrogen acceptance

Reflecting on the configuration of past, ongoing, and emerging national energy transitions [81–84], social acceptance [85–87] – understood as a complex, multi-actor and cross-scalar phenomenon [88–90] where the 'positions' of respective actors are dynamic and continuously evolving [91] – constitutes a precondition for the rapid diffusion of low-carbon energy technologies [89,92,93]. Historically, social acceptance scholarship has focused on socio-political, market, and community acceptance dimensions [94] to reflect people's response to renewable energy technologies [87]. However, in the context of domestic energy adoption [95], it is imperative to include a direct research focus on attitudinal and behavioural acceptance to better understand consumer perceptions, attitudes, motivations, and preferences [26,96–98].

2.2. Insights from systematic literature review and narrative literature review

Despite the recognised imperative to move beyond a predominantly techno-economic focus on the hydrogen transition [99], a comprehensive bibliometric analysis conducted by Kar et al. [9] highlights a pronounced deficit in social science research on the hydrogen economy. Although Kar et al. [9] reviewed 1275 articles on the hydrogen economy, a paucity of research beyond technical areas was strongly reflected by their analysis of keywords, among other metrics such as citation count (see SN2).

Emodi et al. [76] conducted a systematic literature review (N = 43) on hydrogen acceptance studies published between 2008 and 2020, which provides a critical starting point for understanding contributions to date. At the outset it should be highlighted that only five studies in the sample entailed a focus on domestic hydrogen appliances. The review demarcated seven 'determining factor categories' of hydrogen acceptance consisting of aspects such as ***environmental awareness***, ***psychological needs***, and ***economic beliefs***. In total, 30 sub-factors were identified in the review, although this number reduces to 20 when excluding demographic factors. However, it should be noted that *prior knowledge of hydrogen* was included in the list of demographic factors, occurring in 14 of the studies (see SN2).

Subsequently, Scovell [87] reviewed 27 quantitative studies on hydrogen acceptance covering the period 2005–2021 (see SN2), which also reflected a primary focus on hydrogen fuel cell vehicles (HFCVs) and hydrogen fuelling stations (HFSs). The results further demonstrate the potential for differentiating between different aspects of hydrogen

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

acceptance, following the identification of 13 specific factors [87] which in several cases correspond closely to the categorisation presented by Emodi et al. [76].[2]

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

The 14 factors broadly align with previous demarcations,[4] in addition to identifying a set of context-specific factors, such as ***consumer disengagement in energy markets***, ***the lived experience of heating and cooking***, and ***technology choice*** [77] (see SN2). Nevertheless, at the methodological level, the results on domestic hydrogen acceptance presented by Gordon et al. [77] are subject to the same limitation of Scovell [87] in terms of sample size, which reflects the constraints of a narrative literature review in contrast to a systematic review [100].

Most recently, Almaraz et al. [75] conducted a systematic literature review (N = 65) focused on hydrogen research engaging with social aspects (N = 65). The authors [75] identified twelve categories composed of over 40 sub-factors, to which this study partly responds (see Section 5). Notably, ***information*** featured as a top-ranking category composed of several sub-factors: *awareness of carbon footprint*, *awareness of hydrogen*, *communication*, *discourse*, *spreading of information*, *knowledge*, and *education* [75]. However, ***social acceptability***[5] was identified as its own category (ranking 4th) as opposed to the outcome variable or target factor [75]; reflecting the broader focus on the hydrogen economy, as opposed to social acceptance of a specific technology application or range of technologies.

2.3. Insights from focus groups studies and online surveys

In parallel to the review studies summarised in Section 2.2 [73,75–77], primary data collection on hydrogen acceptance has steadily increased. For example, a series of studies have been conducted on consumer attitudes towards HFCVs in India [101–104], alongside follow-up analyses on domestic hydrogen in the UK context [23,105,106].

Through mixed-methods data analysis (i.e. qualitative data and poll data), Gordon et al. [23,105,106] analysed a wide range of previously identified factors through mixed-methods data analysis (see SN3). The research suggested existing gas users are somewhat open to the idea of adopting hydrogen appliances, but have divergent views towards boilers and hobs [23], which is in line with the finding of Scott and Powells [25]. Additionally, respondents expressed stronger support for 'green' (renewable-based) hydrogen compared to 'blue' hydrogen production (i.e. reliant on natural gas and carbon capture and storage) [106], which has proven the case across a range of national contexts [107–109].

Additionally, research in the Australian context has been advanced by Dumbrell et al. [110], Lozano et al. [76] and Bharadwaj et al. [78], as summarised in Supplementary note 3 (see Table S1). Notably, Bharadwaj and colleagues [78] found that respondents' general support for hydrogen depends on their socio-economic characteristics and geographic location, thereby highlighting the importance of consumer heterogeneity. Furthermore, Scovell and Walton [80] conducted in-person focus groups to explore public perceptions of hydrogen energy technologies across the supply chain. However, following a procedure of reflexive thematic analysis, the authors [80] failed to evaluate eight identified acceptance categories in terms of importance. Therefore, it remained challenging within the context of the qualitative analysis to directly estimate whether, for example, risk factors or perceived benefits are more prevalent in the mind of Australian [80]. Relatedly, in some cases, it was somewhat unspecified whether identified factors have a positive, negative, or neutral influence on hydrogen acceptance [80].

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

2.4. Summary of literature review findings

Based on the literature review results, there are three key limitations constraining knowledge on hydrogen acceptance, which this study aims to address. Firstly, research focusing on the residential context is a more recent development [77] and therefore less represented in the literature [76], which this study helps directly address through its stated focus. Secondly, it emerges that previous studies have sometimes conflated or miscategorised acceptance factors leading to a lack of coherence within and between studies, which can be counteracted through a more rigorous approach, as applied in this study (see Section 3). Thirdly, emphasising the importance of consumer heterogeneity is a recent research advancement [23], which may reflect higher levels of support for hydrogen as technology engagement, environmental awareness, and (hydrogen) knowledge levels increase [78,108]. As demonstrated in Section 4.6, exploring the potential for group-specific differences in relation to consumer perceptions represents a focal point of this analysis, which significantly advances the discourse on domestic hydrogen acceptance.

3. Material and methods

This section described the methodology in five stages, which includes firstly reporting the techniques for developing the online survey in Section 3.1 and the multigroup research design in Section 3.2. Next, Section 3.3 provides an overview of the mixed-methods approach to data analysis, while Section 3.4 provides specific details regarding the steps taken to develop a domestic hydrogen acceptance typology. Finally, Section 3.5 reports the statistical procedures carried out to support the multigroup analysis through a comparative assessment of consumer heterogeneity.

3.1. Online survey development

Between October and December 2022, the research team conducted an online survey to examine public perceptions of domestic hydrogen in

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

[3] However, seven studies focused on a range of hydrogen technologies, as opposed to solely the residential context, as evidenced by studies engaging with the Australian hydrogen economy [183,248–250]. Moreover, only six studies were sourced from the academic literature [25,37,181,245,247,251], which underscores the need for wider scholarly engagement, particularly beyond the UK [25,37], European [181,247,251], and Australian context [245].

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

[5] In 1982, Otway and Von Winterfeldt explained that "the social acceptability of large-scale technologies depends upon a wide range of things, some related to safety and economics, but also some factors of cultural, social, and psychological significance" [252].

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

Study	Description of coding procedure(s) applied	Limitations of the coding technique
[76]	• Categorises *distributive benefits* under ***economic benefits***[a] • Assigns *social equity* to ***social influence***	• These sub-factors were assigned to different categories despite sharing a general link to one of three tenets of energy justice [111–113], namely, distributional justice [114,115]
	• *Prior knowledge* was assigned to ***demographic factors***	• However, *environmental knowledge* was assigned to ***environmental awareness***, while the ***psychological needs*** category is unused for sub-factors related to knowledge
[80]	• Presents ***safety and risk perceptions*** as a mixed category	• The category also includes perspectives regarding hydrogen as less risky for people's health compared to conventional fuels, in view of its environmental benefits
	• ***Frames environmental impacts*** exclusively in terms of perceived benefits • ***Water use*** refers to negative impacts related to scarcity issues	• This separation, while justifiable to an extent, raises the question as to whether it would be more logical to subsume both benefits and risks under the same category, while making use of sub-themes or sub-factors as performed by Emodi et al. [76]
	• Frames ***hydrogen competing with other renewables*** exclusively as a risk factor that may delay the low-carbon transition	• Respective hydrogen production pathways may compete with or compliment the deployment of renewables, as evidenced by the UK's twin-track strategy [19,106] and highlighted in a recent case study [49]
[75]	• Demarcates ***socio-political factors*** in relation to *energy security* (N = 10), *equality* (N = 2), *energy justice* (N = 4), *well-being* (N = 6), and other *socio-political factors* (N = 9) • ***Acceptability*** is reflected with an identical sub-factor (*acceptability*, N = 26), while 7 other sub-factors (N = 41) complete the category, with *trust* having the lowest frequency (N = 1)	• Appears to conflate sub-factors belonging to the economic domain and social fairness, while assigning an unspecified generalised category (i.e. other) • The application of a self-reflecting sub-factor, as also applied in the socio-political category, compromises the ability to distinguish between factors that compose the acceptability theme, and thereby partially contaminates the data analysis
	• ***Socio-economic factors*** is composed mainly of *other socio-economic factors* (N = 15), in addition to jobs and labour (N = 6)	• The authors give no explanation of what aspects compose the 'other' category and fail to justify why this approach is taken, whereby the 'other' assignment comprises most of the category
	• ***Research and development*** (N = 19) and ***technological safety*** (N = 14) have no sub-factors	• Both factor categories are composed of their main factors exclusively, which is inconsistent with the approach applied elsewhere in the analysis wherein sub-factors compose each category

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

the UK context. The survey design was informed by findings from literature review (see Section 2) and results from online focus groups carried out in Spring of 2022 [23,105,106]. Accordingly, the survey instruments were informed by qualitative insights [116], which guided the identification of salient acceptance factors [80,117].

Qualtrics software [118] was used to program the survey, which was validated through pilot tests, in addition to feedback rounds from hydrogen experts and social scientists. The survey took approximately 15 to 20 mins to complete and engaged respondents with several aspects of domestic hydrogen acceptance, as reflect by 15 distinct question categories,[6] which included psychological, technological, financial, economic, environmental, safety, and behavioural aspects of domestic hydrogen acceptance, among other factors. All survey items were measured using either a five-point or eleven-point Likert scale.

Acknowledging the content of the online survey at the outset is vital, since most of the identified factors composing the acceptance typology were reflected within the survey question items. To facilitate engagement and more meaningful responses, the survey also included information provision on hydrogen production methods, hydrogen developments in the UK, and hydrogen home appliances (i.e. boilers and hobs) [119].

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

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

In total, around two-thirds of respondents provided a written statement (N = 1213), which the authors initially analysed to derive consumer positions (i.e. hydrogen optimist, hydrogen hopeful, hydrogen curious, hydrogen neutral, hydrogen cautious, hydrogen sceptical, and hydrogen pessimist) on a newly developed 'acceptance matrix' [120].

3.2. Multigroup research design

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

International research has shown that technology and environmental engagement predict consumer acceptance for smart home technologies [121–123], battery electric vehicles [124,125], solar PV [126–130], and residential micro-generation technologies [131] including energy-efficient heating appliances [132]. While these findings appear to hold equally true for hydrogen energy technology acceptance [106,108,133], this study is motivated by the need to consolidate earlier inferences where research methods lacked theoretical rigor [134] or were otherwise constrained by small sample sizes [73].

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

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

Table 2
Consumer sub-groups composing the survey sample.

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

as a reliable proxy to compare economic factors, without the need to set a specific quota for annual income.

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

3.3. Mixed-methods data analysis

To derive statistical inferences from participant statements, this analysis is grounded in an integrated mixed-methods approach [135], whereby qualitative and quantitative contributions are captured within the same study [136,137] to support deeper insights and stronger explanatory power [135].

Qualitative research approaches – relying on textual and other forms of non-numerical data [135,138] – are better suited to generating theories about underexplored phenomena [137], such as renewable energy acceptance [94,139] and emerging low-carbon technologies [26,88,117,140]. By contrast, quantitative research "adopts structured procedures and formal instruments for data collection" [141]. Quantitative analysis adheres to objective and systematic methods which operationalise a given set of variables [141] to measure magnitude and frequency, explore relationships between sub-groups, and test theories [137].

Mixed-methods research should focus strongly on the 'conversation' that develops when qualitative and quantitative research components interact with one another [137]. By establishing a dialogue between both strands [142], mixed-methods analysis seeks to enable "a seamless transfer of evidence across qualitative and quantitative modalities," thereby integrating insights from explanatory descriptions and statistical analyses [135]. Notably, through "understanding the underlying dynamics and meaning-making associated with constructs" [143], qualitative data can provide insights on a given problem that cannot be directly quantified [141].

Through a mixed methods approach drawing on over 1000 responses from the UK public, this study addresses the methodological limitations of previous studies, which can be characterised as follows: (1) lacking primary data due to a reliance on data sourced from literature review [73,75–77]; (2) conducting focus groups analyses constrained by small-sample sizes and an exploratory lens [23,105,106]; and (3), quantitative assessments which can only partially reflect consumer positions and expressions [78,108,110].

3.4. Typology development

Typology development features prominently in fields of psychology and sociology [144], alongside growing research areas such as socio-technical transitions [145]. A typology is developed hierarchically [146] by grouping empirical data into specific categories according to similarities, and indirectly, by way of shared differences [144]. Accordingly, typology development provides a means to examine the homogeneity within and the heterogeneity between sub-groups, so that statistical conclusions can be drawn [142,144]. Success is achieved when one data type (e.g. qualitative statements) produces a specific typology that anchors the analysis within an underlying framework [142].

The broader application of typologies to energy case studies is well documented in the literature. For example, Darmani et al. [147] formulated a comprehensive typology to assess drivers of renewable energy technologies (RETs), whereas Kerr et al. [148] proposed an explanatory typology of community benefits from renewable energy development. More recently, Raška et al. [149] advanced a theory-driven typology of planning decisions associated with land use conflicts, while Frantál et al. [150] combined interview data and statistical analysis to develop an empirically grounded typology of wind energy conflicts. Other researchers have adopted similar systematic techniques to examine clean energy communities [151], eco-innovation and green growth [152], and energy security [153].

The applied methodology reflects the application of hybrid deductive-inductive coding to thematic analysis [154,155], in line with established methods in the social sciences [156,157]. While inductive analysis proceeds without a predetermined theory or framework, the deductive approach rests on processing data in relation to pre-established concepts and themes [158,159], which is guided in this study via the selected survey questions (see Section 3.1). In addition to drawing on a deductive a priori template of codes [160] for hydrogen acceptance factors [77,134], the open-ended nature of the final survey question facilitated a data-driven inductive approach [161], whereby salient factors could emerge from within the data [155,162] and be cross-compared to assess validity [163,164].

In sum, the coding procedure involved five distinct steps which are outlined in Fig. 1 and demonstrated in Section 4.1. Firstly, an acceptance typology was developed from the full dataset of responses (N = 1213), before applying a stricter inclusion criteria. In total, around 88 % of

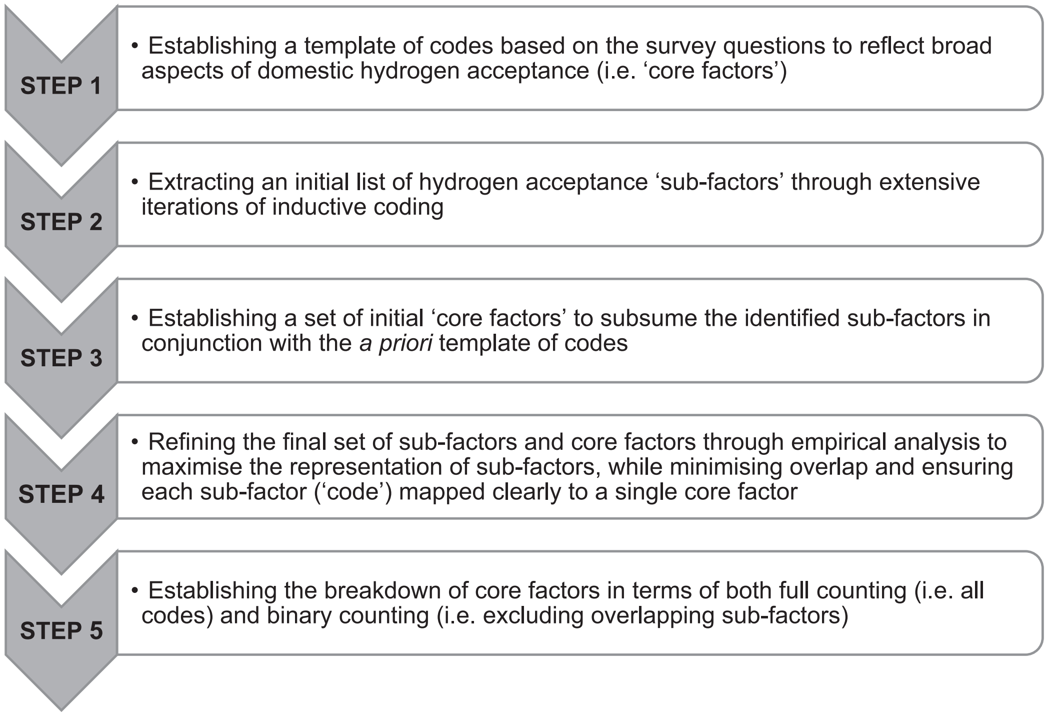

Fig. 1. Coding procedure and research steps for establishing a typology of domestic hydrogen acceptance.

responses (N = 1064) made explicit reference to at least one specific hydrogen acceptance factor, thereby qualifying for further analysis. Critically, the excluded responses (N = 149) relayed more general reflections towards domestic hydrogen [120], without citing a specific factor, or communicating an explicit positive or negative emotion. For example, around two-thirds of excluded statements corresponded to neutral or agnostic perceptions of hydrogen (N = 101). Accordingly, these responses were discarded for the purposes of developing a more definitive acceptance typology, but incorporated in parallel research to reflect a 'hydrogen neutral' position [120].

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

> "*You will still be using the same distribution network pipeline. You won't have to change that. It will just be like when we went from coal gas to natural gas. Most of the old pipeline has been renewed now.*"
>
> (MEG254)

Other infrequently mentioned sub-factors included *energy security risks* (N = 3) and *age barrier* (N = 3), which are defined in Supplementary note 4 (see SN4) alongside all identified sub-factors (48 in total).

3.5. Quantitative analysis of consumer heterogeneity

Categorising and quantifying participant statements marks an iterative process [165,166] of data transformation [116,137,167]; adhering to definitive and transparent steps which can be replicated [168] to promote dialogue between research groups [169]. In terms of quantitative methods, various descriptive statistics were analysed to support the analysis of *sub-factors* of domestic hydrogen acceptance (primary, secondary, and tertiary), which represent a group of ***core factors***.

Thus, the main interest lies in detecting the frequency and scope of response patterns (positive, neutral, and negative) and organising these trends into a robust acceptance typology, which extends from the core level (12 factors) to the sub-level (48 factors). The assessment of group differences is supported by evaluating the relative frequency of response types (i.e. *sub-factors*) across consumer sub-groups, thereby controlling for differences in sample size. Moreover, consumer heterogeneity is further examined through a series of non-parametric tests (Kruskal-Wallis H Test) and post-hoc tests, which are performed in IMB SPSS (version 28.0).

Two post-hoc tests are applied in Section 4.6 to report the adjusted ρ-value (Bonferroni correction) and effect size (*r*). SPSS outputs provide the adjusted ρ-value, which is calculated by diving the original ρ-value by the number of analyses on the dependent variable [170]. *r* is calculated using the following formula, where Z = standardised value for the test statistic; and n = sample size [171]:

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

The following cut-offs are applied to evaluate effect size: small: 0.01–<0.08; moderate: 0.08–<0.26; large: >0.26 [172,173].

Overall, the analytical process adopted in this study involves three main stages: (1) coding the qualitative dataset to establish hydrogen acceptance factors; (2) descriptively and statistically examining the transformed dataset; and (3), synthesising the findings through a coherent narrative which weaves together both strands of evidence [135]. Through these steps, a systematic and rigorous method is implemented to construct a typology of domestic hydrogen acceptance based on extensive qualitative data (see Fig. 2).

4. Results

The results are reported by way of six sub-sections beginning with a breakdown of core factors and sub-factors of domestic hydrogen acceptance in Sections 4.1 and 4.2. Next, Section 4.3 reports the analysis of primary sub-factors, while Sections 4.4 and 4.5 analyse secondary and tertiary sub-factors of domestic hydrogen acceptance. Lastly, Section 4.6 identifies and discusses sub-factors (primary and secondary) which are statistically significant predictors of consumer heterogeneity.

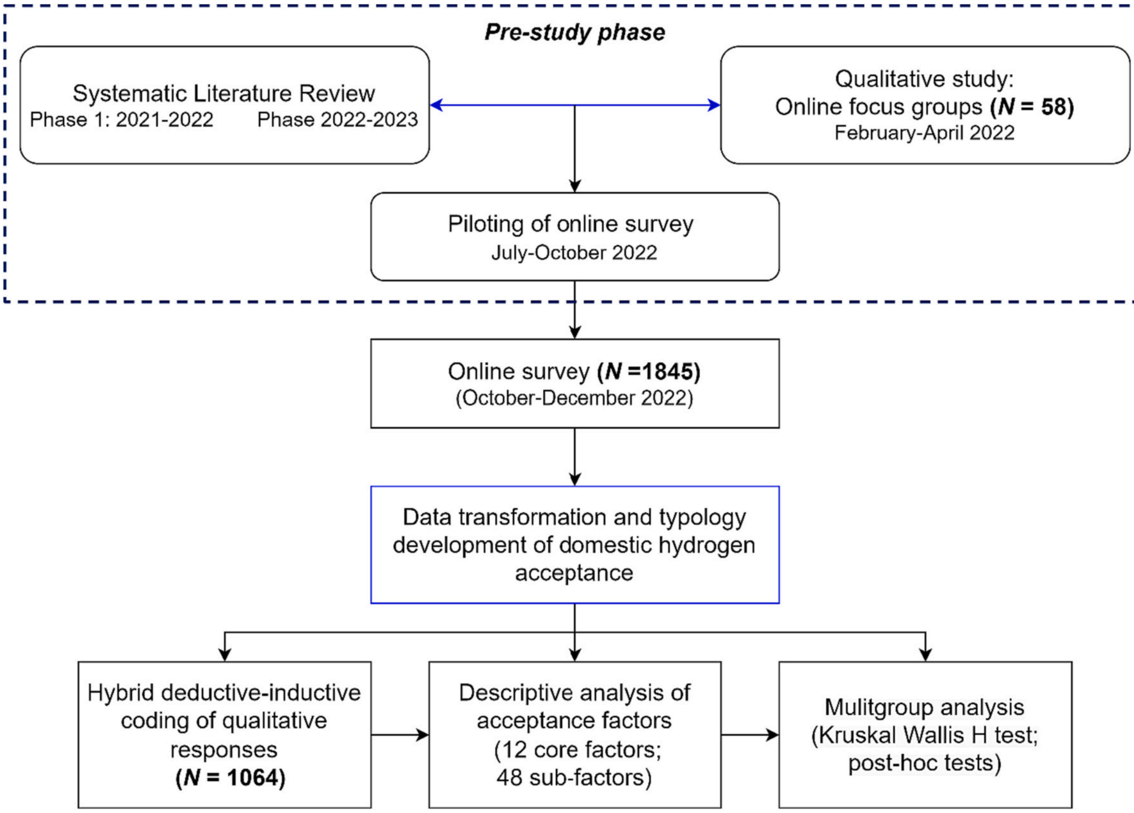

Fig. 2. Mixed-methods research design.

4.1. Core factors of domestic hydrogen acceptance

4.1.1. Results from full counting

In total, 2180 references to specific perceptions of domestic hydrogen were detected across the sample ($M = 2.05$ per respondent; $SD = 1.16$). Overall, the number of references to hydrogen acceptance factors per sub-group deviated only marginally from the sample distribution, which indicates each group was close to equally engaged in the topic. Following the procedure described in Section 3.4, this analysis identifies 12 categories or 'core factors' reflecting consumer attitudes towards domestic hydrogen, which are defined in Table 3. Firstly, the results are evaluated without accounting for areas of overlap within responses at the factor level (i.e. full counting), which enables the composition of each core factor to be clearly demarcated. Secondly, areas of overlap are calculated and factors are discounted (i.e. binary counting) to support a more accurate breakdown of core factors, which provides a basis for comparative assessment in Section 5.

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

The identified core factors were further classified according to a weighting system for clearer demarcation. Half of the group qualified as 'primary' factors, wherein each factor represented >10 % of coding results. Primary core factors accounted for 77 % of responses, whereas the remaining 23 % were classified as 'secondary' factors (<10 % of codes). Among the primary group, information ranked highest (17.7 %), followed by image (13.3 %), finance (12.7 %), affect (12.7 %), environment (10.8 %), and fairness and trust (10.1 %). Among the secondary group, technology (5.0 %), was closely followed by safety (4.8 %), economy (4.7 %), logistics (3.7 %), social (2.5 %), and performance (2.0 %). The results are visualised in Fig. 3 and further illustrated in Fig. 4 based on the data reported in Table 3.[7]

4.1.2. Results from binary counting

In some cases, core factors (i.e. ***safety*** and ***performance***) were composed of sub-factors which had no level of overlap in relation to consumer responses.[8] For the most part, limited overlap occurred between core factors when analysed in terms of full counting and binary counting, except for ***information***, and ***fairness and equity*** (see Table 4).

Information presented high levels of overlap between *knowledge deficit* and *pro hydrogen information* (in general), whereby the former sub-factor motivated requests and desires for learning more about domestic hydrogen (see Section 4.3.1). In terms of ***fairness and equity***, given its composition as a solely negative core factor (see Fig. 4), just over a quarter of responses referred to at least two of seven available sub-factors, with a maximum of three sub-factors described (N = 9). Overall, the number of references reduces from 2180 to 1935 (-11.2 %)

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

[8] For example, in the case of safety, respondents either recognised *safety benefits* or *safety risks*, or otherwise stated that their attitude was *contingent on safety implications*, which resulted in three mutually exclusive sub-factors (1 positive, 1 neutral, and 1 negative).

Table 3
Summary of core factors of domestic hydrogen acceptance.

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

Source: Author's compilation with definitions adapted from [73,134,174,175].

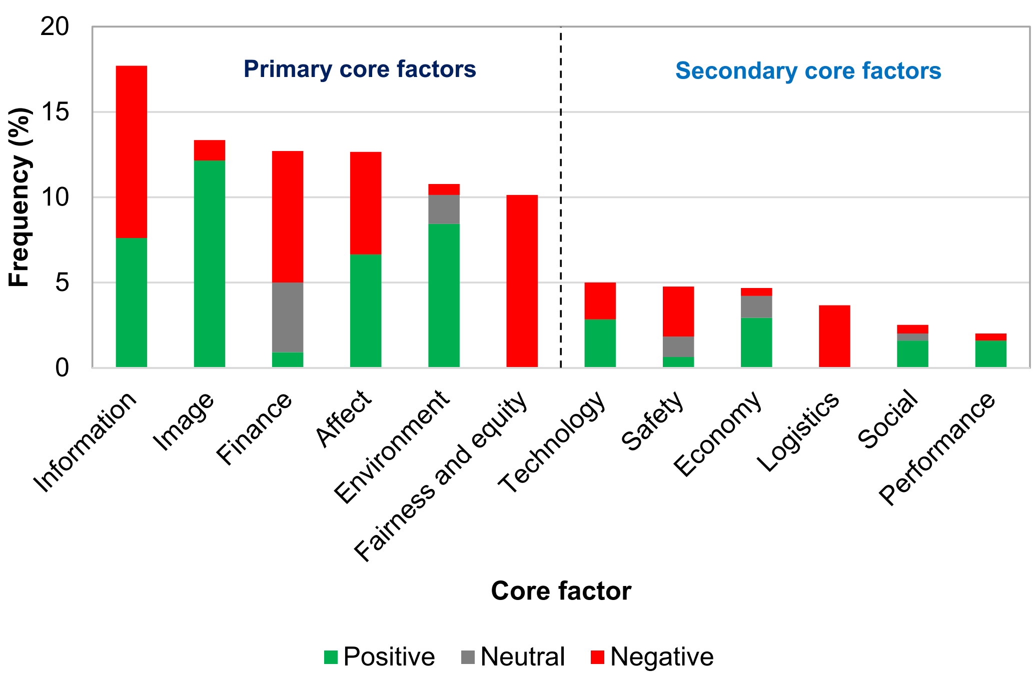

Fig. 3. Breakdown of core factors of domestic hydrogen acceptance (full counting).

when applying binary counting.

As a result, the rank order of factors presented in Fig. 5 deviates somewhat from Fig. 3, giving rise to an alternative classification scheme: primary core factors (≥10 % of binary codes); secondary core factors (5–10 % of binary codes); and tertiary core factors (≤5 % of binary codes). Consequently, primary, secondary, and tertiary core factors represent 67.4 %, 18.9 %, and 13.7 % of the coding results, respectively.

The main change reflected in Fig. 5 is near equivalence between the top four primary core factors, namely, ***image*** (14.5 %), ***finance*** (13.9 %), ***affect*** (13.5 %), and ***information*** (13.4 %), while ***environment*** is slightly less represented (12.0 %). At the individual level, ***information*** drops from first rank to fourth when evaluated at the binary level, whereas five core factors only undergo an adjustment of one position, while the remaining six factors remain unchanged. As a result, there is limited impact on the lower ranking core factors, however, there is clearer grounds for demarcating between the secondary and tertiary level, as reflected in Fig. 5 (see SN5).

Adhering to the classification scheme and distribution criteria presented in 4.1.1 (see Table 3 and Fig. 3), Section 4.2 explores the composition and significance of core factors of domestic hydrogen acceptance, which are discussed in terms of respective sub-factors. The critical findings presented in Fig. 5 support the analysis in Section 5, which compares findings from this study to results in the literature.

4.2. Sub-factors of domestic hydrogen acceptance

In total, 48 sub-factors were identified, corresponding to a mean of four sub-factors per core factor (*SD* = 1.41). Specifically, each core factor consists of a minimum of two sub-factors (i.e. for ***affect*** and ***performance***), while seven sub-factors represents the upper limit (i.e.

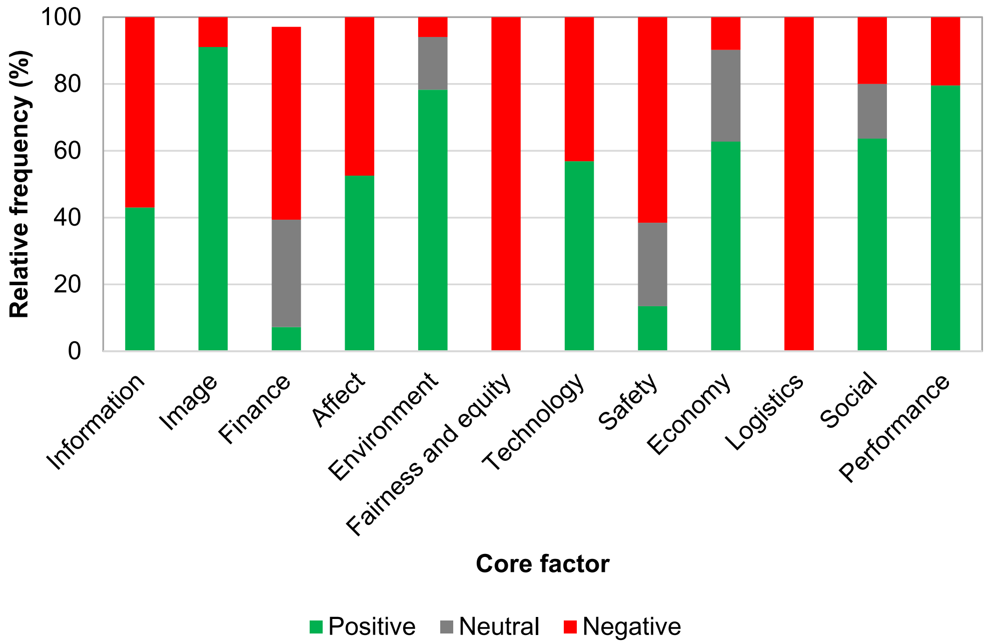

Fig. 4. Weighted analysis of core factors of domestic hydrogen acceptance (full counting).

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

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

fairness and equity). As reported in Table 3, the sub-factors were close to equally balanced in terms of positive (45.4 %) and negative (45.9 %) composition, while neutral responses accounted for a smaller proportion of the retrieved codes (8.7 %).

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

The results of the neutral category are described in Supplementary note 6 (see SN6), given that such perceptions should, in theory, evolve over time to form a positive or negative perception. While neutral perceptions could technically remain recalcitrant or potentially become more widespread overtime, this study concentrates foremost on exploring the main drivers and barriers to domestic hydrogen acceptance. However, an exception is the sub-factor *conditional on cost-of-living crisis*, which is a predictor of consumer heterogeneity and therefore discussed in Section 4.6.2.

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

4.3. Analysis of primary sub-factors

Primary sub-factors of domestic hydrogen acceptance account for 57.2 % of the coding results. Five positive sub-factors compose 59.0 % of the group, while three negative sub-factors account for the remainder. Overall, this breakdown corresponds to 33.8 % and 23.4 % of the coding results. *Knowledge deficit* (10.1 %) represents the most prominent sub-factor, while *fuel of the future* qualifies as the least important, just above the cut-off (5.05 %). The mean frequency for the primary group is 7.2 % (*SD* = 1.54), with three sub-factors falling above this value (*knowledge deficit*, *environmental benefits*, and *financial risks*).

In summary, the primary group represents five core factors, namely, ***information*** (×2), ***environment*** (×1), ***finance*** (×1), ***image*** (×2), and ***affect*** (×2). Accordingly, taking the cumulative contribution of primary sub-factors, the following breakdown is observed across the group: ***information*** (16.7 %), ***affect*** (12.6 %), ***image*** (12.0 %), ***environment*** (8.5 %), and ***finance*** (7.4 %). This sequence retains the top five core factors illustrated in Table 3, with ***information*** preserved as the leading core factor, as reflected by *knowledge deficit* in Fig. 6.

4.3.1. Knowledge deficit and pro hydrogen information

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

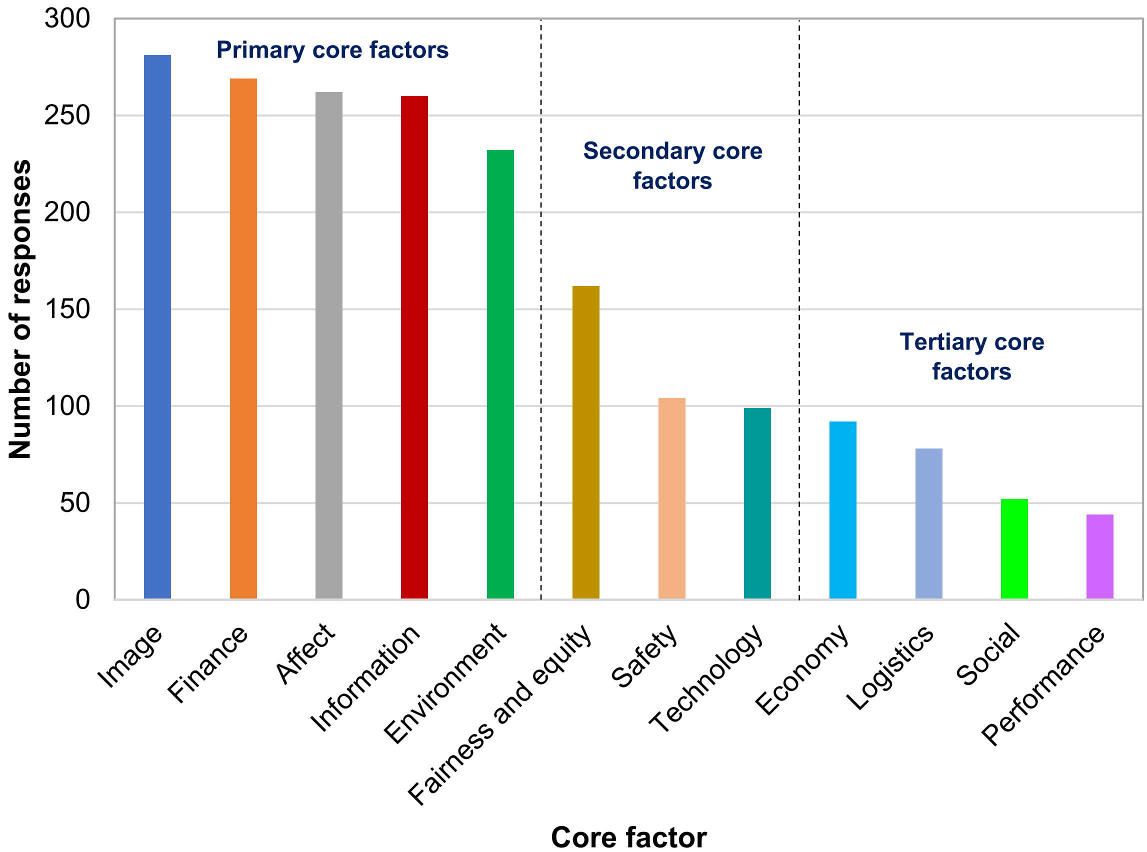

Fig. 5. Breakdown of core factors of domestic hydrogen acceptance (binary counting).

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

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

Multiple studies have highlighted risks and knowledge gaps around hydrogen energy systems, with an emphasis on technical and market barriers [176], the unpredictability of global supply chains for key components [177], as well as lack of skilled labour for scaling up development [178,179]. Above all, the results support previous findings highlighting an underlying knowledge deficit for hydrogen technologies across a range of national contexts [107,110,180,181]. For example, in the Australian context, Scovell and Walton [80] reported a mean subjective knowledge score of 2.33 ($SD = 1.12$) as measured on a seven-point Likert scale.[9] Similarly, following data collection in Spring of 2022 (N = 4372), the UK government reported relatively low levels of hydrogen awareness ($M = 2.44$, $SD = 1.11$) as measured on a five-point Likert scale [182].

While a public knowledge deficit is somewhat pervasive but may also be declining over time [183], consumers also have an expressed preference for learning more, as reflected by a *pro hydrogen information* perspective (N = 143), which in some cases corresponded to specific requests for information on safety and costs (see Table 6 and Fig. S3). Comments included a mix of admissions and affirmations such as the following: "*I don't know enough to form a complete opinion, but I will look into it more*" (BLG90); "*I'm still very new to the concept but will definitely be learning more*" (BLG171); "*I do need to be more informed on the subject*" (BLG73); and "*I am going to do more research*" (BLG61). In some cases, respondents also expressed a more explicit desire, for example, "*I would love to learn more about it*" (BLG164).

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

4.3.2. Environmental benefits

Environmental benefits ranked as the second primary sub-factor and first in terms of positive sub-factors, with around three-quarters of references (N = 137) linking more explicitly to hydrogen's potential impacts (i.e. beyond a generic comment such as 'good' or 'better' for the environment). To an extent, direct references to planetary impacts mirrored the overall discussion of environmental benefits (see Section 4.6.1), whereby the MEG (N = 46) and VEG (N = 40) accounted for nearly two-thirds of references (62.8 %), while the BLG (N = 26) and FSG (N = 25) accounted equally for the remainder of responses.

Several sub-codes emerge following analysis of qualitative response patterns, which in many cases share degrees of similarity or overlap. For example, regarding hydrogen's potential role in decarbonisation,

[9] 1 = 'never heard of hydrogen energy technology', and 7 = 'very knowledgeable'.

Table 6
Breakdown of factors of domestic hydrogen acceptance.

Core factors	Sub-factors	Classification	Count and percentage
Information	• Pro information about domestic hydrogen in general	• Positive	• 143 (6.6)
	• Knowledge deficit	• Negative	• 220 (10.1)
	• Pro information about hydrogen costs	• Positive	• 18 (0.8)
	• Pro information about hydrogen safety	• Positive	• 5 (0.2)
Image	• Fuel of the future	• Positive	• 110 (5.0)
	• Pro hydrogen concept	• Positive	• 154 (7.1)
	• Town gas experience	• Positive	• 1 (0.0)
	• Unpublicised status of hydrogen	• Negative	• 17 (0.8)
	• Negative social representation	• Negative	• 9 (0.4)
Finance	• Financial benefits	• Positive	• 20 (0.9)
	• Financial risks	• Negative	• 160 (7.3)
	• Conditional on financial implications	• Neutral	• 89 (4.1)
	• Boiler rejection due to recent investment	• Negative	• 7 (0.3)
Affect	• Positive emotions	• Positive	• 145 (6.7)
	• Negative emotions	• Negative	• 131 (6.0)
Environment	• Environmental benefits	• Positive	• 184 (8.4)
	• Environmental risks	• Negative	• 9 (0.4)
	• Net-zero scepticism	• Negative	• 5 (0.2)
	• Conditional on environmental implications	• Neutral	• 37 (1.7)
Fairness and equity	• Choice deficit	• Negative	• 28 (1.3)
	• Trust deficit	• Negative	• 28 (1.3)
	• Profit motives of energy companies	• Negative	• 13 (0.6)
	• Consumers shouldn't pay for the costs of the domestic hydrogen transition	• Negative	• 30 (1.4)
	• Government should pay the costs of the domestic hydrogen transition	• Negative	• 20 (0.9)
	• Energy companies should pay the costs of the domestic hydrogen transition	• Negative	• 21 (1.0)
	• Distributional injustice (general)	• Negative	• 81 (3.7)
Technology	• Pro technology or modern progress	• Positive	• 36 (1.7)
	• Pro Research & Development for hydrogen	• Positive	• 26 (1.2)
	• Pro alternative low-carbon options (not hydrogen)	• Negative	• 12 (0.6)
	• Risk aversion to new technologies	• Negative	• 21 (1.0)
	• Hydrogen perceived as an unproven technology	• Negative	• 14 (0.6)
Safety	• Safety benefits	• Positive	• 14 (0.6)
	• Safety risks	• Negative	• 64 (2.9)
	• Conditional on safety implications	• Neutral	• 26 (1.2)
Economy	• Economic benefits	• Positive	• 21 (1.0)
	• Economic risks	• Negative	• 4 (0.2)
	• Energy security benefits	• Positive	• 43 (2.0)
	• Energy security risks	• Negative	• 3 (0.1)
	• Conditional on cost-of-living crisis	• Neutral	• 28 (1.3)
Logistics	• Age barrier	• Negative	• 3 (0.1)
	• Disruptive impacts	• Negative	• 16 (0.7)
	• Logistical risks	• Negative	• 61 (2.8)
Social	• Community benefits	• Positive	• 3 (0.1)
	• Societal benefits	• Positive	• 32 (1.5)
	• Societal risks	• Negative	• 11 (0.5)
	• Conditional on societal implications	• Neutral	• 9 (0.4)
Performance	• Efficiency or utility benefits	• Positive	• 35 (1.6)
	• Efficiency or utility losses	• Negative	• 9 (0.4)

respondents referred to *green energy*, *sustainable fuel*,[10] *clean energy*, *alternative fuel*, and *renewable energy*. In total, nine themes were identified (see Fig. 7), with *climate change* ranking first, whereas *carbon emissions* placed fourth.

Interestingly, relatively few participants made explicit reference to *net zero*, which may reflect a lower level of consciousness and engagement with this term among the public. By comparison, around double the number of respondents articulated the need to *save the planet*.[11] This planet-centric perspective towards hydrogen or "*long-term, save the planet kind-of-feeling*" (MEG 157) was described vividly by one respondent:

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

By contrast, other respondents looked towards a sustainable future with economic growth, which could foreseeably prove incompatible with climate change targets [184,185]:

> "*It has potential to have a significant impact not only on this country but globally too. We are currently in unseen circumstances, so hydrogen-powered options seem like something that is sustainable and allows growth moving forward.*"
>
> (MEG 176)

4.3.3. Financial risks

Consistent with qualitative results [105] and literature review findings [77], *financial risks* associated with the purchasing and running of hydrogen appliances emerged as the third most critical sub-factor of domestic hydrogen acceptance. Epitomising concerns over this aspect, one fuel poor respondent cautioned, "*I cannot afford to heat my house, let alone think about replacing a boiler, which I still haven't finished paying off since I got it replaced*" (FSG 40). Foremost, consumers facing fuel poverty may be forced to prioritise cost considerations above other factors when considering domestic hydrogen adoption.

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

> "*I would not be happy paying towards this as it is going to be incredibly costly. Given we are in a cost-of-living crisis, I'm not sure where the government think people will get the money from when they can't even pay their gas bills or get their boiler serviced*!"
>
> (BLG 166)

Drawing attention to financial, as well as equity-related barriers [49], opposition to the prospect of hydrogen boilers and UK policy was voiced on the following grounds: "*…vastly expensive and ignores the reality of the older UK housing stock. I'm not paying 10k for a boiler, so not heat for me, although I'll be expected to subsidise others*" (BLG 346). Taken as a snapshot, these remarks flag the likelihood, if not inevitability, that domestic hydrogen acceptance will boil down to financial considerations for a significant proportion of society [186].

4.3.4. Pro hydrogen concept and fuel of the future

In terms of image, *pro hydrogen concept* ranked as the fourth primary sub-factor, while *fuel of the future* ranked tenth. The former sub-factor refers to responses citing positive prospects for hydrogen in the long-

[10] More general references to 'sustainability' were also subsumed under this category.

[11] A minority of respondents also referred to saving the world, or even the universe, which was subsumed under this category.

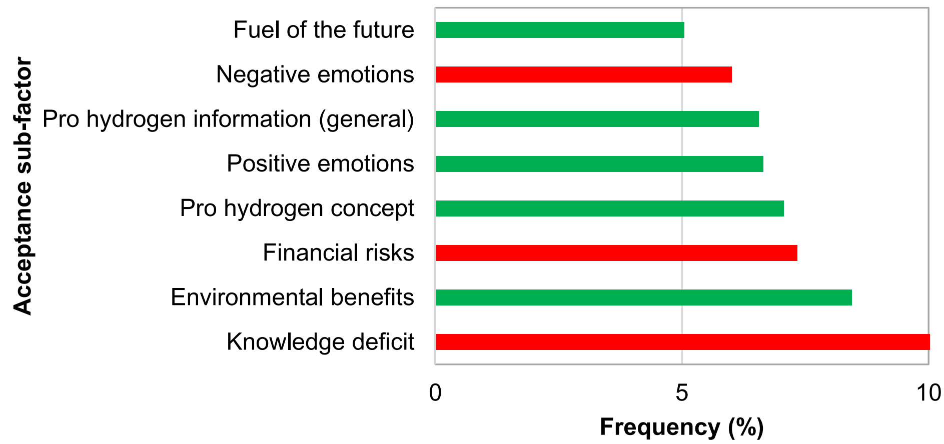

Fig. 6. Primary sub-factors of domestic hydrogen acceptance.

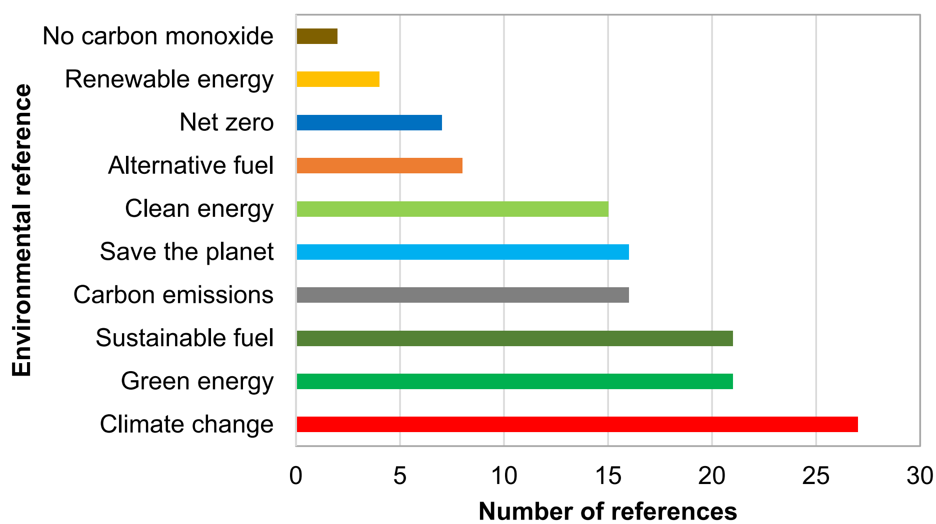

Fig. 7. Distribution of consumer responses citing specific aspects of environmental benefits.

term, often referring to its definitive role as a future fuel. By contrast, the latter sub-factor corresponds to responses citing the positive value of hydrogen, as a general concept for potentially supporting the energy transition.[12] In the Australian context, Scovell and Walton [80] noted a similar perspective in acknowledging that "some [focus group] participants thought that using more hydrogen seemed like a future solution as there needs to be more technological progress," which also links to the positive secondary sub-factor, *pro technology or modern progress*.

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

Regarding the concept of hydrogen homes, a fuel poor participant shared their optimism as follows: "*I think this is a great idea and will hopefully reduce energy bills and the over reliance on rogue states who we rely on at the moment for our gas and energy needs. Great, simply fantastic*" (FSG 91). Among the VEG, respondents shared similar lines of thought, for example, "*I think that introducing hydrogen into homes is a good idea and will boost the economy as well as the environment*" (VEG 98), and "*I think this is an amazing idea and it will help the UK develop a lot!*" (VEG 100). Other notable statements included, "*I think it is a great idea and hope it comes to my local area*" (VEG 86), and "*…very good idea and the government should give more details about it on TV so we are aware*" (VEG 194).

4.3.5. Positive emotions and negative emotions

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

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

Around half of all negative responses were communicated in terms of

[12] Primary sub-factors shared minimal overlap, with eight responses citing both aspects, thereby inferring a predominantly positive social representation of domestic hydrogen. By contrast, only nine responses reflected a negative social representation of hydrogen homes (see Table 6 and Fig. S3).

'concern' or 'worry', which were coded separately to reflect the language used by respondents. Other notable feelings included *confusion*, *nervousness*, and *fear* (see Fig. 8), whereas expressions of *scepticism* or *pessimism* were more limited. Excluding concern and worry, responses which were close synonyms were subsumed under one specific emotion, for example, *nervous* included 'apprehensive', 'hesitant', 'reluctant', 'uncomfortable', and 'uneasy', while fear included 'afraid' and 'scared'.

One respondent illuminated their concerns as follows:

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

Another respondent shared a range of worries:

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

Negative emotions also originated from fears of the new and unknown, "*feel quite nervous thinking about, probably because it's something new*" (BLG 37), while another respondent reflected further on the unfamiliarity of hydrogen fuel [187]:

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

4.4. Analysis of secondary sub-factors

Following the primary category, 15 secondary sub-factors of domestic hydrogen acceptance account for 29.5 % of the coding results (see Fig. 9). Six negative sub-factors compose 45.3 % of this group, whereas five positive sub-factors and four neutral sub-factors account for 26.7 % and 28.0 %, respectively. Taken together, secondary sub-factors represent nine core factors: ***economy*** (×2), ***environment*** (×1), ***fairness and trust*** (×4), ***finance*** (×1), ***logistics*** (×1), ***performance*** (×1), ***safety*** (×2), ***society*** (×1), and ***technology*** (×2).

4.4.1. Positive secondary sub-factors

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

Survey responses linked to aspects of ***performance***, ***economy***, and ***finance*** reflect how the sub-par efficiency performance of the UK housing stock [26,188], coupled to the ongoing energy and deepening fuel poverty crises [105,189–191], will shape consumer expectations for the hydrogen switchover. For example, performance expectancy for domestic hydrogen [134] was framed as follows: "*I want it as a more sustainable alternative to gas and assume it would perform better than electric heating and hobs*" (VEG 103); and "*I consider hydrogen gas more efficient in our daily lives*" (VEG 62).

Interestingly, one respondent perceived hydrogen as a better option over electric alternatives, "*…this means the least disruption and modifications to a house at the moment that currently uses gas*" (VEG 143). Additionally, a fuel stressed participant declared, "*it's clear that hydrogen is an efficient energy source that should be cheaper for consumers than gas,*" (FSG 134) while another respondent shared an optimistic outlook, "*I am looking forward to finally living and bringing up my daughter in a safer and more efficient home*" (BLG 66).

It follows that consumer acceptance will be partly dictated by the degree to which hydrogen can secure a more efficient and reliable energy supply to UK homes, as a potential means for alleviating fuel poverty and economic hardship. However, realising the promise of a national hydrogen economy [192] will rest heavily on the pace at which a domestic hydrogen supply chain can be established, alongside addressing other market barriers and a range of techno-economic, technical, social, and political barriers [26]. Speaking to the need for technological progress, some respondents also cited the need to intensify *research and development* for hydrogen (N = 26), or otherwise expressed general optimism for advancing a more socio-economically viable future by investing resources in the hydrogen economy [75].

4.4.2. Negative secondary sub-factors

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

4.4.2.1. Logistical risks. ***Logistical risks*** accounted for close to 3 % of all references to acceptance factors, placing fourth among the secondary group of sub-factors (see Fig. 9). Notably, participants flagged concerns about the techno-economic feasibility of the switchover concerning cost

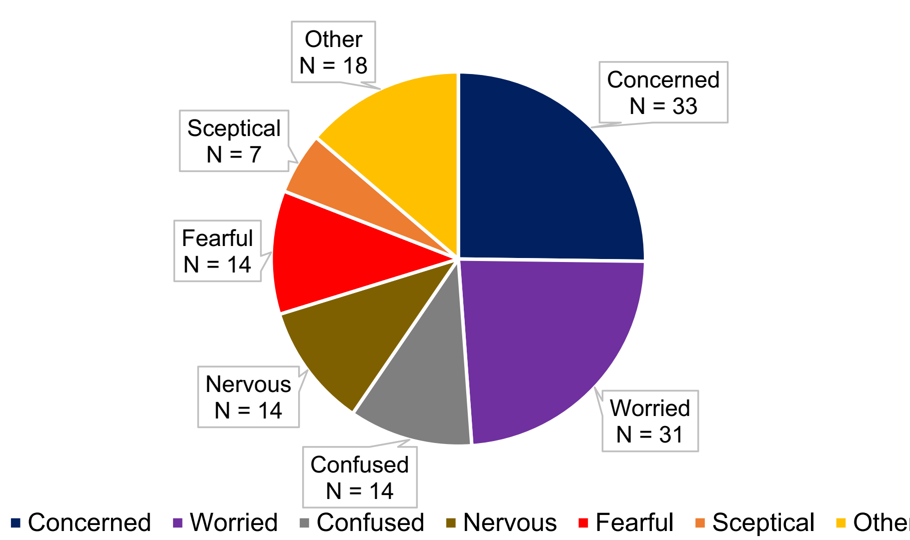

Fig. 8. Distribution of negative emotions across the sample (N = 131).

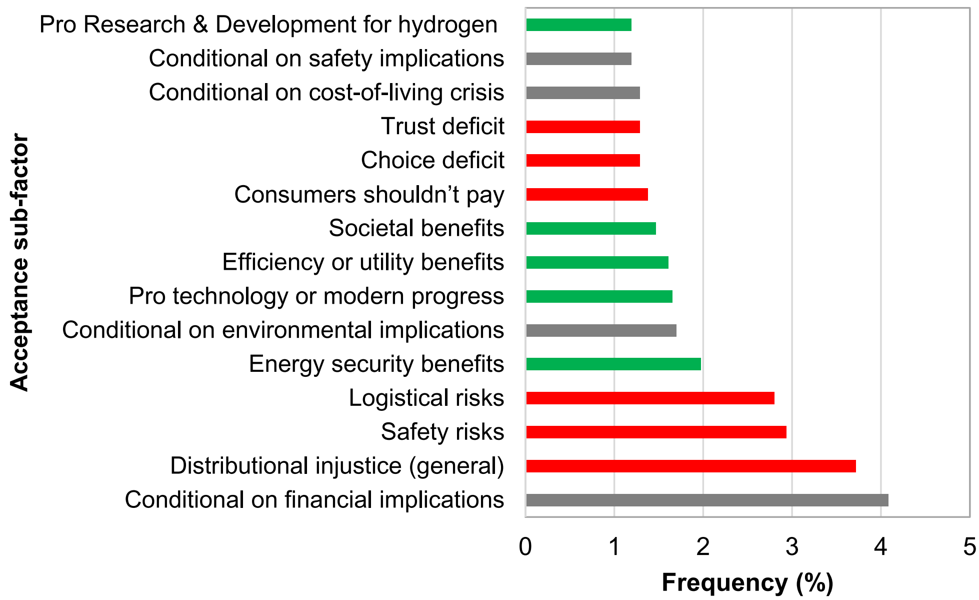

Fig. 9. Secondary sub-factors of domestic hydrogen acceptance.

factors and scalability [49], describing hydrogen homes as, "*a potentially good solution with many technical and infrastructure challenges to be overcome*" (MEG 1), which "will *present a major engineering and logistical challenge costing billions*" (MEG 119).

Both the scale and cost of the challenge were highlighted in other remarks, for example, "*insufficient supplies to switchover and in the end, consumers have to foot the bills*" (BLG 193), and "*seeing as big schemes bring big mistakes is my main concern…it's a good energy but installing it across the country is the worrying point*" (BLG 293). Other respondents were sceptical or critical about potential energy requirements, "*it seems to be a technology worth exploring, but the case for it is far from compelling due to the high energy required to produce it*" (MEG 195) and "*it will need more electricity to generate hydrogen*" (FSG 132). Relatedly, one respondent saw advantages with other energy sources, "*I feel like as much as hydrogen is a viable future energy source, I do feel that nuclear and renewables are a lot more feasible and cost efficient*" (VEG 64).

Another participant noted advantages in targeting better insulation for homes ahead of adopting low-carbon technologies, "*might be useful to insulate homes first*" (MEG 222), while one respondent noted the challenge related to market factors, "*…needed for the future but will take some time to adapt business models*" (VEG 168). Both points are on the radar of UK policy makers [193], with the Heat and Buildings Strategy [21] calling for measures to improve the thermal efficient of homes such as draught-proofing and other types of insulation, while the government is actively pursuing a certification scheme to help build transparency and confidence across the hydrogen sector [194]. Overall, this study suggests that the disruptive impacts of the domestic hydrogen transition are a moderate factor in shaping consumer attitudes, which is in line with prior findings in the UK context [105,195].

4.4.2.2. Safety risks. Reflecting the extant narrative concerning technical barriers to implementation [49,196–198], *safety risks* associated

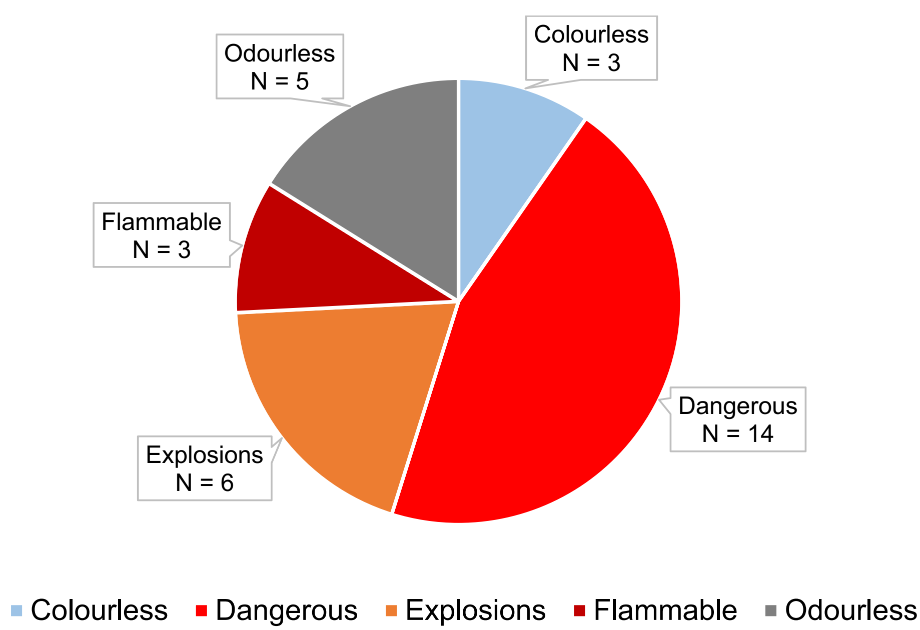

Fig. 10. Distribution of responses citing specific risk perceptions around hydrogen safety.

with hydrogen were cited over four times more frequently than *safety benefits*. From the 62 references to safety concerns, around half concentrated on particular risk perceptions, with most respondents describing hydrogen as *dangerous*, while some specified these dangers in terms of explosions and high flammability (see Fig. 10).

Overall, safety-related concerns were associated with hydrogen's inherent characteristics as a highly flammable, colourless, and odourless gas [199], which led to outright rejection among some respondents. One respondent felt "*not very comfortable with something so flammable*" (MEG 151), while another was "*fearful of explosiveness*" (VEG 26), with a third citing further reservations, "*…safety wise I would be reluctant to use this… the images of the hydrogen balloons igniting come to mind*" (MEG 242). This respondent was not alone in expressing a negative social representation. For example, other responses linked hydrogen to nuclear power, "*I always associate hydrogen with nuclear, probably why I am not overly enthusiastic*" (MEG 44), and "*…still unsure, like before fearful of nuclear explosion*" (FSG 177).

Regarding the characteristics of hydrogen, one respondent noted a technical issue which the scientific community are invested in resolving, through the addition of odourants as well as colourants [24,47,200]: "*the only slight concern I have is the fact it is odourless, so I am unsure if people would be able to detect gas leaks through smell*" (VEG 184). Additionally, one technically minded participant was "*concerned about safety and the problems of brittleness when components are exposed to hydrogen over an extended period*" (VEG 17), whereas a baseline respondent felt "*scared as no controls appear to be in place for safety issues*" (BLG 290).

While several technical solutions are foreseeable [176,201–203], negative safety perceptions must be addressed and overturned if hydrogen is to have a place in the future energy mix beyond industrial applications [28]. Otherwise, the following perception could prevail among wider society ahead of more substantive evidence, "*from what I understand, hydrogen is very dangerous, and it wouldn't be advisable for use in the general public*" (MEG 24).

4.4.2.3. Perceptions of fairness and equity. ***Fairness and equity*** concerns accounted for 26 % of secondary sub-factors, focusing primarily on aspects of *distributional injustice* [204,205]. Insightfully, one participant articulated their concerns in significant detail, contextualised to the discussion around industrial reinvigoration [105] and the North-South divide [206,207]:

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

Another respondent from the BLG also captured these concerns succinctly:

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

Such perspectives affirm that stakeholders will need to mitigate the risks associated with distributional injustice to facilitate a socially acceptable transition to hydrogen homes [26]. These risks will be heightened when a *trust deficit* is present among consumers and if they perceive a lack of choice (i.e. *choice deficit*) regarding the prospective transition to hydrogen homes (see Section 4.5), as highlighted via online focus groups with UK participants [105].

Regarding the costs of the domestic hydrogen transition, several respondents believed *consumers shouldn't pay*, while others specified that *the government* and/or *energy companies should pay*. Notably, placing the financial onus of the hydrogen switchover on energy companies links directly to an associated tertiary sub-factor, namely, *profit motives of energy companies* (see Section 4.5).

Grievances towards profiteering were cited across all sub-groups, suggesting that this phenomenon threatens hydrogen acceptance irrespective of one's personal status. Moreover, a greater number of respondents raised further issues linked to aspects of energy injustice [111], such as lack of consent (procedural injustice) [208] and hardships incurred by vulnerable households (recognition injustice) [209], among other matters concerning social fairness (see Table 7). These risks will be heightened when a trust deficit is pervasive among consumers, coupled to perceptions of a lack of choice regarding the prospective transition to hydrogen homes [105].

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

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

Further concerns were cited around choice and procedural injustice, "*I think consent is a vital issue here, as in, people shouldn't be made to pay for things if they don't want them*" (BLG 140). Another respondent cautioned, "*there needs to be more information, especially regarding other energy sources such as underground heat pumps in order to make fully informed decisions*" (BLG 328). Concerns over decision-making aspects were particularly emphasised, "*It's very worrying but it's likely that these decisions will be taken by central government which means the public will not have a say in the matter*" (BLG 232), and "*…people shouldn't be forced to have it*" (BLG 240). As reported in Table 8. The main trust deficit expressed among respondents pertained to the shortcomings of the UK government, with no shortage of pessimistic and sceptical remarks.

Table 7
Consumer perspectives citing aspects of energy injustice.

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

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

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

4.5. Analysis of tertiary sub-factors

A group of 25 sub-factors – each with a frequency of <1 % – account for the remaining responses (13.3 %). Foremost, 17 negative factors represent 68.5 % of tertiary level responses, compared to 28.4 % for positive responses and 3.1 % for the single neutral sub-factor (i.e. *conditional on societal implications*), as reported in Supplementary note 7 (see SN7).

All core factors were represented within the tertiary group except for ***affect***. ***Economy***, ***fairness and equity***, ***image***, ***social***, and ***technology*** featured most prominently, represented by three respective sub-factors. Next, ***environment***, ***finance***, ***information***, and ***logistics*** were represented by two sub-factors each, while ***performance*** and ***safety*** featured a single sub-factor. Foremost, the above distribution highlights how a multitude of potential barriers could shape domestic hydrogen acceptance across different parts of society.

Within the tertiary group, several sub-factors were identified which could prove more prevalent across parts of the UK population, depending on relevant socio-structural and contextual factors [77]. For example, the *profit motives of energy companies* [210] is an increasingly polemic issue [211,212], given the cost-of-living crisis [189,190], and recent economic climate in the UK [213,214].

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

By extending the discussion beyond primary and secondary sub-factors of domestic hydrogen acceptance, this part of the analysis further demonstrates how a multitude of different variables may operate to varying degrees (see SN7); as shaped by underlying spatio-temporal and socio-historical factors [26,87,140], and the context-specific nature of domestic energy acceptance [91]. Having reviewed the breakdown of core and sub-factors across the sample, Section 4.6 extends the analysis by determining which factors influence consumer heterogeneity.

4.6. Predictors of consumer heterogeneity

To derive additional insights into the configuration of consumer preferences and the influence of salient acceptance factors, Section 4.6 examines the foremost predictors of consumer heterogeneity. The analysis involves examining statistical differences between sub-groups

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

Respondent ID	Illustrative statements
BLG 22	• *Cost is critical, people need to have a choice when it comes to financial commitments. Subsidising the cost using corporation tax would help people.*
BLG 358	• *We shouldn't be paying to put huge profits into different energy companies.*
BLG 363	• *With billions of pounds in profit, the costs could be covered by the main beneficiaries - the energy companies.*
MEG 107	• *I like the idea of using hydrogen as alternative to current gas. I believe it should be the current gas suppliers that should contribute to the changes to the infrastructure and switchover, not general public. They already have huge profits as it is.*
MEG 153	• *I'd love the chance to use this power source, but I also think that the costs should be shared by the power companies as they will ultimately benefit from sales/profits.*
MEG 155	• *If government/taxpayer funded, private companies should not profit from it.*
MEG 199	• *It sounds like something else for the energy companies to make more money out of the customer and bills will go up even more!*
MEG 254	• *The energy companies that run the distribution networks and British Gas make enough profits to pay for it.*
VEG 50	• *I am concerned that there is so much emphasis on householders paying for this. Why is there no suggestion that energy companies should be stumping up for the majority of the conversion from the excess profits they are currently in receipt of. The order of priority always seems to place householders at the top of the list.*
VEG 129	• *It's going to be expensive, but the energy company should accommodate the cost.*
VEG 182	• *The costs of any change over should be met by the companies that will receive obscene future profits.*
FSG 179	• *The energy companies are making vast profits. They should fund this.*
FSG 195	• *Those making a profit from sales should pick up the tab for implementing.*

by accounting for all sub-factors classified as primary or secondary, while tertiary sub-factors are excluded due to sample size constraints (see Table A1 and Fig. S3).

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

To capture these dynamics, Fig. 11 illustrates the reported sub-factors according to relative frequency between sub-groups, wherein *environmental benefits* ranks first ($\rho \leq 0.001$) and positive emotions ranks last ($\rho = 0.079$). Accordingly, the group is composed of the following core factors: ***environment*** (×1), ***information*** (×1), ***finance*** (×1), ***fairness and equity*** (×2), ***economy*** (×2), and ***affect*** (×2). Additionally, Fig. 12 extends the analysis by comparing the relative importance (i.e. total number of references) of each sub-factor across consumer segments, wherein *knowledge deficit* ranks first and *choice deficit* ranks last. Notably, *choice deficit* does not register as a sub-factor for the VEG (see Section 4.6.2).

Taken together, Figs. 11 and 12 highlight which aspects of domestic hydrogen acceptance could resonate distinctly across parts of the population, and thereby lead to different response patterns and outcomes, both within and between different regions of the UK such as the Northwest and Northeast of England where activities for hydrogen trials have been targeted [19].

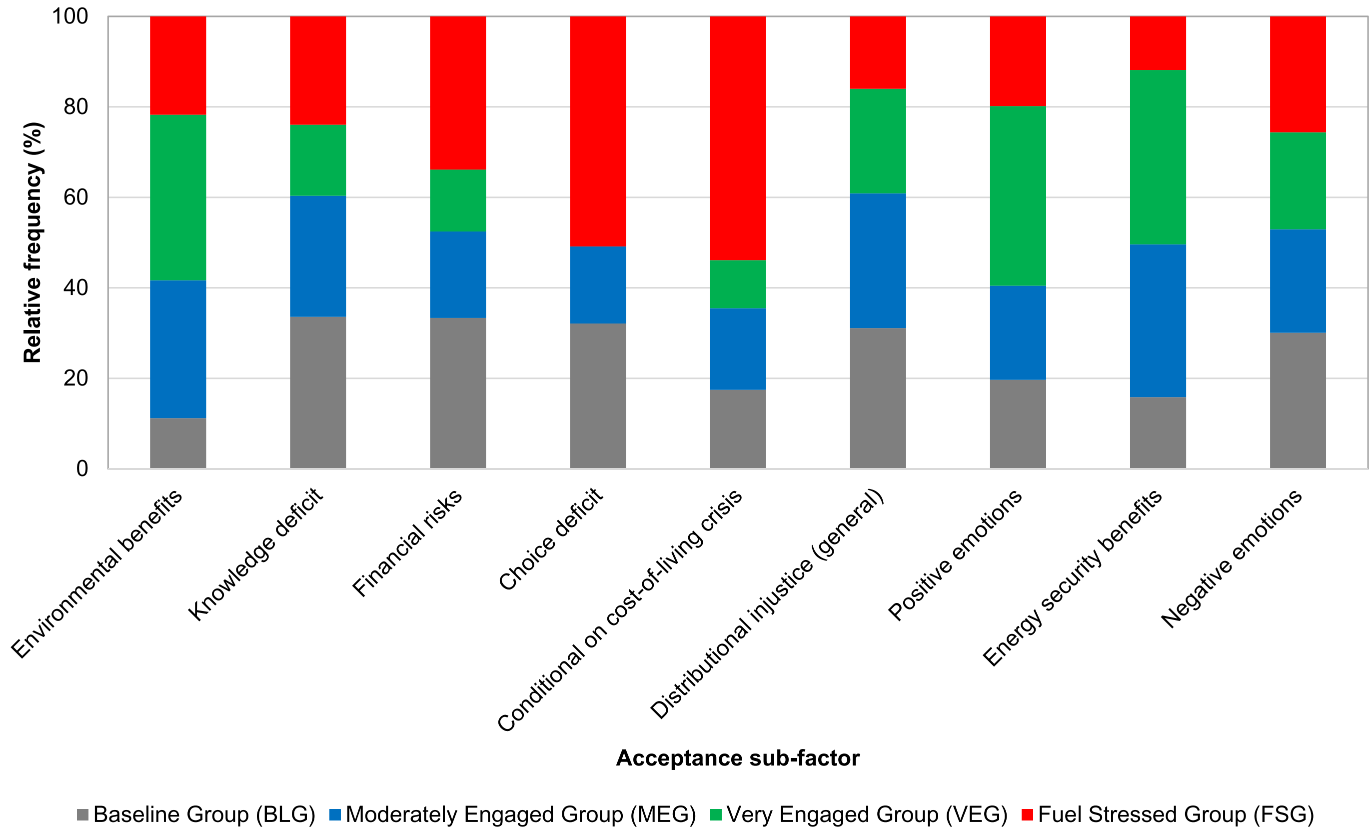

Fig. 11. Sub-factors of domestic hydrogen acceptance explaining consumer heterogeneity ranked according to statistical significance.

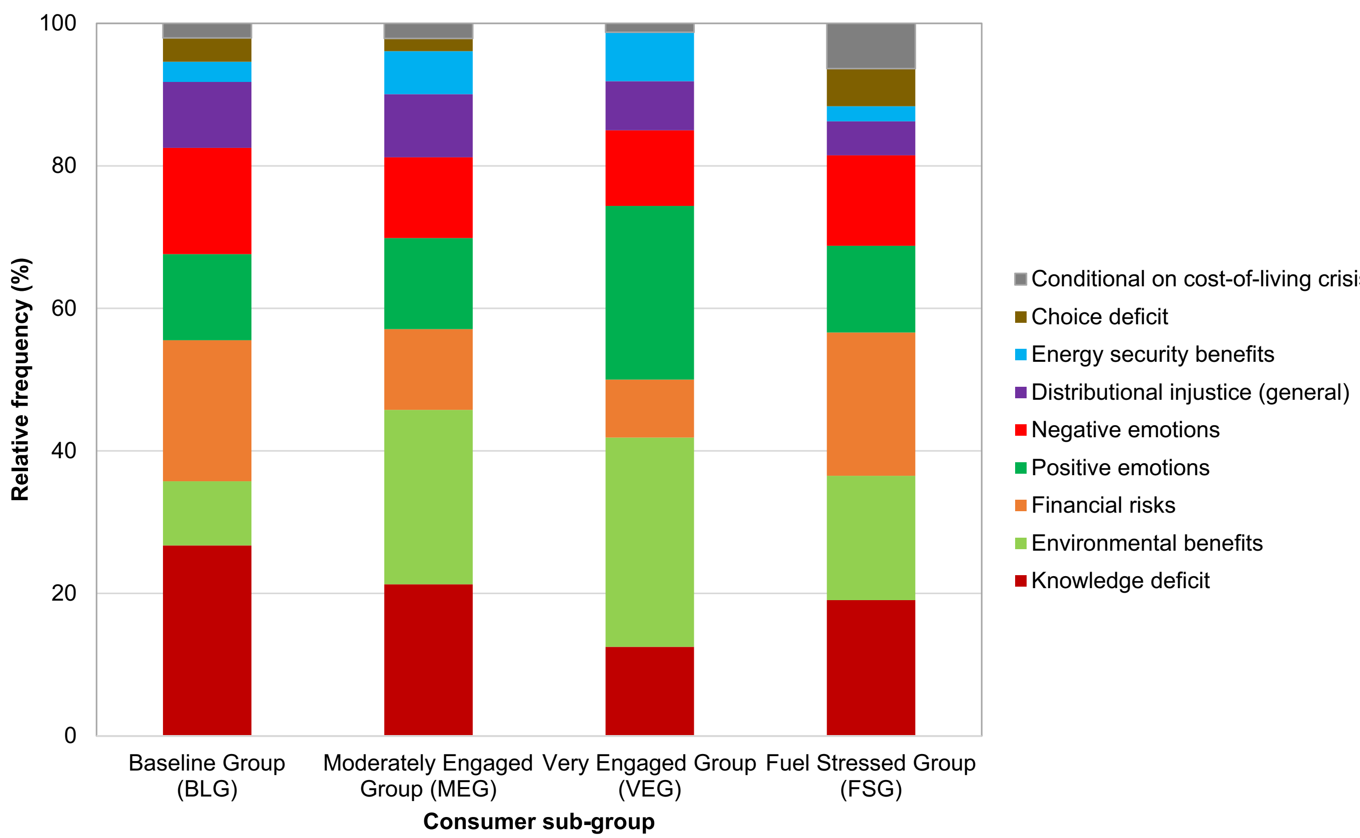

Fig. 12. Sub-factors of domestic hydrogen acceptance explaining consumer heterogeneity according to relative distribution within sub-groups.

4.6.1. Divergence in perceptions of primary sub-factors

Following a Kruskal-Wallis H test, *environmental benefits* (N = 184) emerged as the foremost sub-factor responsible for observed group differences across the sample: H (3, N = 1064) = 32.517, $\rho \leq 0.001$. The median ranks for each group were as follows: BLG: *Md* = 491; MEG: *Md* = 574; VEG: *Md* = 562; and FSG: *Md* = 523. Consequently, statistically significant differences were observed between three pairwise comparisons: BLG and MEG; BLG and VEG; and FSG and MEG (see Table 10). It follows that engagement in renewable energy technology and the environment have a positive association with perceived environmental benefits of hyrogen homes.

As the foremost negative sub-factor, *knowledge deficit* (N = 220) accounted for the second highest level of variance across respective subgroups: H (3, N = 1064) = 29.304, $\rho \leq 0.001$. Statistically significant differences were observed between the following groups: BLG and VEG, BLG and FSG, MEG and VEG (see Table 10). The observed relationship affirms a positive association between hydrogen knowledge and environmental and technology engagement [108,215–217], whereby the VEG had the lowest knowledge deficit (*Md* = 474).

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

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

These patterns held partially true when considering negative emotions, which were transmitted foremost by the BLG (Md = 550) and least by the VEG (Md = 511), whereas the MEG (Md = 529) and FSG (Md = 527) had a comparable median rank score. It follows that the BLG and VEG were distinct from one another in terms of negative feelings (ρ = 0.054). Overall, the VEG proved the most positive and least negative consumer segment (see Table 10). Thus, the comparative analysis reveals contrasting emotional responses between the VEG and BLG, whereas the MEG and FSG were close to equally balanced in this regard, as illustrated in Figs. 11 and 12. Further implications regarding observed differences between consumer sub-groups, including the positive influence of technology and environmental engagement on domestic hydrogen acceptance, are explored in Supplementary note 8 (see SN8).

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

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

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

4.6.2. Divergence in perceptions of secondary sub-factors

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

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

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

Finally, in terms of references to equity and fairness, participant statements focused on issues of *distributional injustice* (N = 81) – not specified to related objections regarding the costs of the hydrogen transition[13] – ranked sixth as a predictor of consumer heterogeneity: H (3, N = 1064) = 8.804, $\rho = 0.044$. Generalised comments on issues of distributional injustice were most pronounced among the BLG (*Md* =

[13] I.e. *consumers shouldn't pay for the costs of domestic hydrogen, the government should pay*, *energy companies should pay*, and *the profit motives of energy companies*.

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

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

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

544), followed by the MEG (*Md* = 540), VEG (*Md* = 520), and FSG (*Md* = 515). However, given the lack of consistency between moderately and very environmentally and technology engaged respondents, it is instructive to analyse response patterns in comparison to all aspects of ***fairness and equity*** (N = 221). Accordingly, Fig. 13 provides a means for better distilling differences between groups to reflect the interrelated and compounding nature of energy injustice.

Drilling down suggests that distributional injustice is a key concern across all sub-groups. However, it is noteworthy that the FSG flagged general equity issues with a low frequency due to a higher concentration around specific aspects of distributional injustice (see Figs. 12 and 13). Foremost, fuel stressed respondents feel the responsibility of paying for the domestic hydrogen transition should rest on the shoulders of government, whereas the MEG attribute stronger levels of accountability to energy companies, especially in view of their sustained profit margins.

In summary, ***fairness and equity*** ranks ahead of most sub-factors, excluding *environmental benefits*, *knowledge deficit*, and *financial risks*, in predicting consumer heterogeneity, as reflected by the following result: H (3, N = 1064) = 13.363, $\rho = 0.004$. Concerns related to fairness and equity were least pronounced among the VEG (*Md* = 489) and most visible among the BLG (*Md* = 558), with the MEG proving marginally less concerned (*Md* = 531) than the FSG (*Md* = 533). Consequently, the disparity between the BLG and VEG proved significant at the 1 % level (see Table 11), which may also be attributed to the VEG having the highest income levels among all sub-groups [120], as further discussed in Supplementary note 8 (SN8).

4.6.3. Summary of statistical findings

Overall, this analysis identifies five primary sub-factors and four secondary sub-factors which predict consumer heterogeneity to varying degrees. As illustrated in Figs. 11 and 12, the foremost sub-factors explaining group differences are *environmental benefits*, *knowledge deficit*, and *financial risks*, which are also the top three ranking factors in terms of total references across the sample (see Fig. 6). It emerges that environmental, informational, and financial dimensions of domestic hydrogen are fundamental to the emerging contours of social acceptance, while aspects of fairness and equity linked to *energy injustice* are also highly significant. Furthermore, emotional responses reflect underlying heterogeneous attitudes towards hydrogen homes, which may ultimately dictate public sentiment [134].

The results imply that negative emotions may reflect greater divergence in hydrogen perceptions than positive emotions. This is a potentially critical finding since contestation and scepticism have recently dictated the trajectory of domestic hydrogen futures in the UK context [218–220]. Specifically, in July 2023, a planned village trial for Whitby village in Ellesmere Port (Cheshire) was cancelled by the UK Minister for Energy Efficiency and Green Finance (Lord Callanan) [221]. The

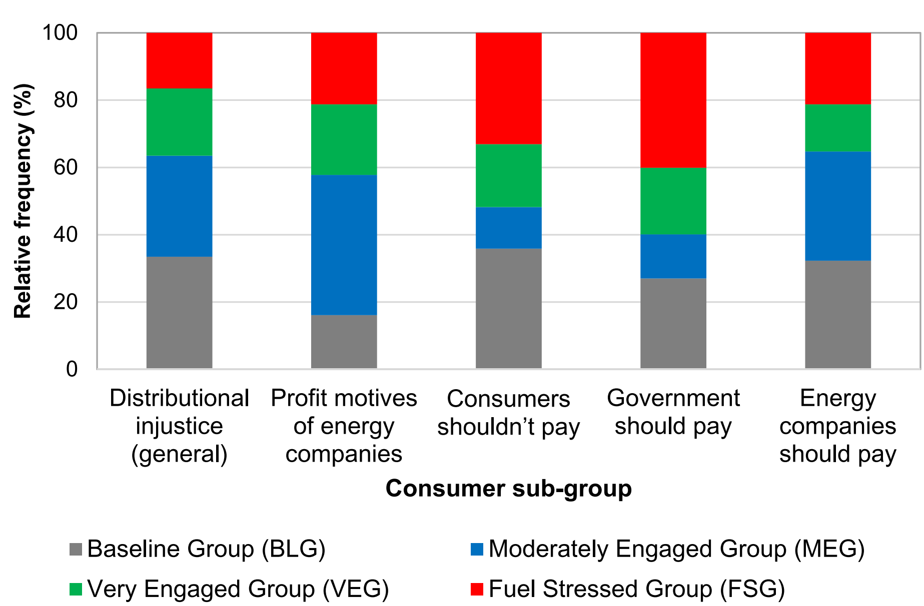

Fig. 13. Comparison of distributional injustice sub-factors across consumer sub-groups.

decision stemmed largely from a pronounced trust deficit and perceived lack of choice among residents, alongside other perceptions of distributional injustice, which culminated in local opposition to hydrogen homes [222–224]. Critically, around 10.3 % of the Whitby population experience fuel poverty [225], 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) [226]. Consequently, socio-demographic factors may have exacerbated a sense of reluctance among parts of the Whitby village population towards the prospect of trialling hydrogen homes.

5. Discussion

This section firstly discusses the implications of sub-factors, following the analysis undertaken in Sections 4.2–4.6. Thereafter, a further exploration and comparative analysis of core factors is discussed to advance the findings presented in Sections 2 and 4.1.

5.1. Leveraging opportunities to promote hydrogen acceptance

At present, a pervasive knowledge deficit may undermine the feasibility of securing social acceptance for the domestic hydrogen transition. This threat is amplified in view of the association between consumer scepticism towards hydrogen technologies and a lack of knowledge and awareness [227,228]. However, consumers are also eager to learn more about hydrogen homes (see Section 4.3.1), which includes interest in financial aspects of the transition and safety implications (see Table S3). As a result, deploying hydrogen homes will require implementing strategic measures to first raise the knowledge and awareness of the technology across society.

Additionally, heightened concerns over fairness and equity may precipitate negative emotional reactions such as fear, worry, and scepticism, which would undermine prospects for developing a national hydrogen economy. Foreseeably, such emotions could be partially offset by if consumers become more technology and environmentally engaged over time [120], while addressing concerns around financial risks, distributional injustice, a lack of choice, and safety-related risks. Furthermore, consumer responses may shift from resistance or ambivalence, towards tolerance or acceptance [26], if environmental benefits are tangible and effectively communicated [195]. In an ideal scenario, risk factors and perceived costs would gradually be transformed into perceived benefits, or at least neutralised, through public engagement campaigns.

This analysis entails a strong focus on primary sub-factors of domestic hydrogen acceptance, in view of their prevalence (see Fig. 6) and influence in predicting consumer heterogeneity (see Figs. 11 and 12). However, it should be emphasised that secondary and tertiary sub-factors together account for nearly 43 % of the coding results. This weighting reinforces the importance of understanding public perceptions across a range of aspects, especially in view of the strong representation of negative sub-factors beyond the primary level. For example, respondents cited various risks linked to technical and infrastructure challenges (see Section 4.4.2.1), which could otherwise constrain the speed and scale of the domestic hydrogen transition. Additionally, context-specific perspectives and emerging factors such as appliance age and energy security risks (see Section 4.5 and Fig. S3) should also be internalised into decision-making processes.

An advantage of this study is the advancement of deep insights into the emerging contours of consumer heterogeneity, which transmit the importance of adjusting policy prescriptions and public engagement strategies to meet the needs and expectations of specific consumer segments. Accordingly, domestic hydrogen acceptance would likely be strengthened across society by taking concrete measures to build support among fuel poor communities and fuel stressed households. For example, policies should aim to ensure fuel poor consumers do not incur disproportionate financial risks or marginalisation in terms of technology choice and involvement in the transition. Therefore, definitive action is needed to restore a greater sense of social trust in the government and energy sector [105]. While social acceptance is widely regarded as a precondition to scaling up emerging energy technologies, social trust is critical to supporting the necessary enabling conditions for securing public support.

5.2. Strategic targeting of hydrogen acceptance dimensions

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

An instructive starting point for devising a more strategic focus – grounded in empirical data – lies with analysing the evidence base reviewed in Section 2 (see SN9). Among the reviewed materials, four studies [75,77,134,195] engage with at least 10 acceptance factors and can therefore support comparative analysis. Each study critically evaluated and ranked identified acceptance factors according to descriptive or statistical analysis. Additionally, the study of Almaraz et al. [75] presents results from both full counting and binary counting, thereby providing an additional opportunity for extracting comparative insights (see Tables S4 and S5). However, it should be noted that Almaraz et al. [75] reviewed studies on the hydrogen economy (N = 65), while Gordon and colleagues [134] analysed studies on (general) hydrogen acceptance (N = 33), whereas the two remaining articles engaged specifically with domestic hydrogen acceptance [77,195]. Consequently, the comparative analysis is limited to a partial representation of consumer attitudes towards hydrogen homes.

The analytical procedure involved evaluating the sub-factors reported in each study and recoding the results to match the typology employed in Fig. 3. In several cases, there was close overlap or direct crossover between the core factors identified in this study and terminology used in other analyses (see Tables 1 and S1). This similarity reflects the notion that the proposed acceptance typology is strongly grounded in findings from literature review (see Section 2). However, this study is the first to identify ***image*** as a core factor of domestic hydrogen acceptance (see Fig. 14), relaying the extent to which hydrogen's social representation will likely shape public perceptions [229].

Additionally, it is noteworthy that ***image*** is the only core acceptance factor ranking within the primary group that fails to account for group differences.[14] It follows that when expressed, a positive social representation of hydrogen may prove relatively homogenous across different parts of the population. However, recent developments in Whitby village have transmitted to increasingly negative representations of hydrogen in the mainstream media [220,230,231]. As a result, there is palpable apprehension regarding the current socio-political legitimacy of prospective hydrogen trials [26].

This apprehension is reflected by increasing pressure for a public vote regarding a planned hydrogen village trial in Redcar (Yorkshire) [232], which may be downgraded in size if approved by the government [233].[15] These developments reflect an emerging negative social representation concerning domestic hydrogen in areas designated for local trials. Foremost, the research community should also respond by formally analysing the role of social representation in shaping attitudes towards hydrogen homes, as reflected *by* ***image*** as the first ranking core factor when calculated via binary counting (see Fig. 5).

Notably, ***financial*** is predominantly a high ranking or primary

[14] Similarly, it can be inferred that, except for ***economy***, the remaining secondary core factors –***technology***, ***safety***, ***logistics***, ***social***, and ***performance*** (see Fig. 3) – are also composed of relatively homogenous sub-factors.

[15] In December 2023, the Redcar trial was cancelled by the UK government.

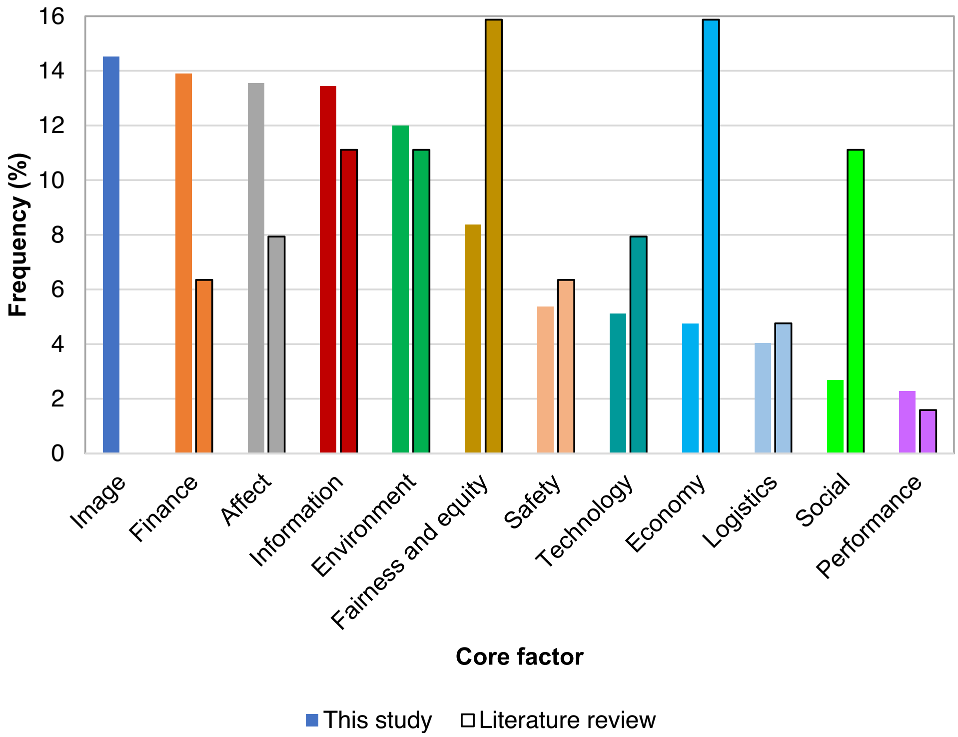

Fig. 14. Comparison between core factors of domestic hydrogen acceptance identified in this study and literature review.
Results from this study are presented by the first bars.
Literature review results are distinguished by a dark blue border.

factor, as is ***environment***. However, ***fairness and equity*** is a mid-ranking factor, whereas ***technology*** and ***safety*** are typically mid-to-low ranking factors. Nevertheless, across the four reviewed studies [75,77,134,195] it is challenging to extract consistent patterns (see Table 12), which likely reflects the different methodologies applied such as systematic literature review [75,134], narrative literature review [77], and structural equation modelling [195].

An additional mode of analysis is to compare the total frequency of core factors identified within the small sample (N = 4) to the results of this study, as shown in Fig. 14. In some cases, there is close convergence between the literature findings and ranking of core factors presented in Fig. 5. Specifically, ***information***, ***environment***, ***safety***, ***logistics***, and ***performance*** have similar levels of representation. However, to date, ***finance*** and ***affect*** are significantly underexplored within the literature compared to the importance levels reflected in this study. This observation highlights the need to increase research efforts to better

Table 12
Comparative analysis of core factors of hydrogen acceptance across the literature.

Rank	This study (binary counting)	[77]	[195]	[75] (full counting)	[75] (binary counting)	[134]
1	IMG	FIN	SOC, ECON, ENV	INFO, LOG	FIN	ENV
2	FIN	INFO	AFF	FIN	INFO, LOG	SOC, ECON, ENV
3	AFF	LOG	ENV	FIN, F&E	ECON	SOC, ECON, ENV
4	INFO	F&E	F&E	SOC, ECON, ENV	FIN, F&E	F&E
5	ENV	TECH	AFF	ECON	F&E	SFTY
6	F&E	TECH	LOG	F&E, ECON	F&E, ECON	SOC, ECON, ENV
7	SFTY	SFTY	SOC, ECON	F&E	F&E	TECH, PERF
8	TECH	ENV	SFTY	F&E	SOC, ECON, ENV	INFO
9	ECON	F&E	INFO	F&E	SOC, ECON	INFO
10	LOG	F&E	INFO	SOC, ECON	TECH	FIN
11	SOC	F&E		TECH	F&E	AFF
12	PERF	AFF		SFTY	SFTY	AFF
13		ECON				INFO
14		TECH				

Grey = Affect (AFF); Light blue = Economy (ECON); Green = Environment (ENV); Gold = Fairness and Equity (F&E); Orange = Financial (FIN); Blue = Image (IMG); Red = Information (INF); Pale blue = Logistics (LOG); Mauve = Performance (PERF); Pale orange = Safety (SFTY); Bright green = Social (SOC); Teal = Technology (TECH).
In study [77], the rank order is derived by qualitative assessment of findings in the literature (N = 17).
In study [195], the rank order is derived via the effect size (f 2) of acceptance constructs in a partial least squares structural equation model (N = 1845).
In study [75], the rank order is derived via frequency of occurrence in reviewed studies (N = 65).
In study [134], the rank order is derived via frequency of occurrence in reviewed studies (N = 33).

understand the financial and emotional dimensions of domestic hydrogen acceptance.

It is further suggested that ***economy***, ***fairness and equity***, and ***social*** are somewhat over-represented in studies to date, when contextualised according to their potential influence in shaping hydrogen perceptions. On the one hand, this result may reflect the fact that only two of the four studies had an explicit focus on hydrogen homes. Evidently, studies engaging with the broader hydrogen economy necessitate a stronger focus on socio-economic aspects [74], while the need to address issues of 'hydrogen justice' is increasingly recognised among the research community. [209,234,235]. Consequently, instances of what may be otherwise misconceived as research bias can be largely explained and justified. Critically, the main priority should be to address areas of under-representation, as neglecting key acceptance factors in future studies would lead to a degree of stagnation in advancing the international evidence base. By contrast, numerous studies on issues such as hydrogen justice can serve to further enrich the growing evidence base by stimulating new insights.

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

If further classified according to the schema presented in Fig. 5, it follows that ***techno-economic*** and ***social representation*** compose the primary category, while ***emotional***, ***psychological***, and ***environmental*** comprise the secondary category, with ***ethical***, ***technological***, and ***safety*** constituting the tertiary level of acceptance dimensions. This marks a novel contribution in disseminating the potential influence of drivers of domestic hydrogen acceptance based on extensive qualitative evidence sourced from primary data collection.

Among a range of key insights, the analysis reflects the likelihood that ethical aspects concerning the deployment of hydrogen homes are a comparatively lower priority when faced with more immediate financial risks, which aligns to the findings presented in Table 12. It also telling that technological and safety dimensions rank lowest, which likely reflects a general expectation that switching to hydrogen boilers and hobs would approximate a close substitute for existing gas appliances [23,195].

This study finds limited evidence that the disruptive impacts of the switchover process are more than a moderate concern or secondary sub-factor (see Section 4.4.2.1), which somewhat contradicts the narrative portrayed by Thomas et al. [186], following deliberative workshops carried out in Wales, as well as the findings of Lozano et al. [108] in the Australian context. An explanation for this discrepancy may be the inclusion of a greater number of acceptance (sub-)factors in this analysis, which in turn approximates a more accurate comparative evaluation. However, this analysis aligns with prior findings [77] including the study of Thomas and colleagues [186], by highlighting the extent to which financial risks weigh strongly on the mind of UK households. Critically, financial perceptions reflect the ongoing impacts of the energy crisis [105]. Notably, the current socio-economic environment reflects the emergence of *conditional on the cost-of-living-crisis* as a predictor of consumer heterogeneity, following a higher response rate from fuel stressed respondents.

6. Conclusions

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

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

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

Firstly, information dissemination must adhere to bridging a specific knowledge gap surrounding environmental, financial, and safety implications, among other factors such as appliance performance [23,73,236]. Relatedly, the results affirm the importance of strengthening hydrogen's image or social representation in the public consciousness, as a tractable commercial technology and long-term sustainable fuel. Consequently, prospects for transitioning homes to hydrogen and advancing the national hydrogen strategy will hinge firmly on public perceptions of perceived environmental and socio-economic benefits [195]. Foremost, there is an increasing imperative to deliver targeted communication campaigns and demonstration projects, which are grounded in principles of procedural, distributional, and recognition justice [105].

In view of recent events in Ellesmere Port [223], key stakeholders such as gas distribution network operators, alongside central policy makers and local government representatives, must act decisively to restore a greater sense of trust in the country's energy strategy and political process [105]. The government and energy sector should take decisive action to overcome mounting trust deficits, and public concerns over inequality and socio-economic deprivation [105]. Absent of these measures, hopes for hydrogen homes [192] could otherwise be deflated indefinitely and derailed in a way reminiscent to fracking in the UK [237,238]. The imminent risk is that negative imagery associated with hydrogen boilers and hobs could spread or 'spillover' [239] to other parts of the hydrogen economy [5,209]; threatening efforts to decarbonise industrial sectors and transport applications [28,240], which would put a stranglehold on visions for a net-zero society [241].

Although the case of hydrogen homes may appear somewhat isolated, both in technological terms and geographically [26], decisions on domestic hydrogen are likely to have a ripple effect across parts of the national hydrogen economy. Regional events in the UK could also hold potential global implications for technology diffusion and climate change targets. Regardless of broader spillover effects, it is apparent that public perceptions of domestic hydrogen [20,186] and the ensuing discourse on residential decarbonisation [193] will shape ambitions for realising a net-zero society.

While the domestic hydrogen transition remains at an early stage and is currently contested [186,242], findings from this study can enrich the evidence base on consumer attitudes towards residential decarbonisation. The results apply directly to the domestic energy context [25], but also hold critical lessons for other sectors of the economy such as transport [243] and industry [244]; wherein local communities and end-users are set to interact with hydrogen energy systems and associated technologies [73,110,245].

Whether focused on the context of hydrogen homes, or other hydrogen technologies and low-carbon energy sources, this study transmits the benefits of distilling consumer acceptance and heterogeneity through an empirically-grounded typology. Accordingly, the proposed acceptance typology presents significant opportunities for further exploration and can be advanced by drawing on larger datasets in future survey studies. Critically, researchers should further unpack the potential relationship between social trust and consumer choice in shaping hydrogen acceptance. Checking the validity of the statistical findings should be taken forward as a focal point of future research, which can target a more in-depth understanding of perceptions of fairness, equity, and justice in relation to hydrogen homes (see Fig. 13).

Additionally, follow-up studies should further examine secondary and tertiary core factors and associated sub-factors of domestic hydrogen acceptance. This focus will contribute towards validating observations from the UK context as retrieved during the winter of 2022. The aim should be to facilitate a longitudinal evidence base, as achieved to an extent by Martin et al. [183] in the Australian context, and Yap and McLellan [246] in Japan. In parallel, there are increasing opportunities for cross-country analysis, which should be leveraged to support previous studies on HFCVs in the European context [181,247].

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

CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

We have attached our data in an excel file. We have also attached the SPSS equivalent where the various tests were performed.

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Appendix A

The nine acceptance sub-factors discussed in Section 4.6 are highlighted in **bold**. Tertiary sub-factors explaining consumer heterogeneity are highlighted in ***bold italics*** (N = 8).

Table A1
Statistical results for differences across the sample regarding sub-factors of domestic hydrogen acceptance.

Core factor	Acceptance sub-factor	*p*-Value
Information	Pro information about domestic hydrogen in general	0.556
	Knowledge deficit	**<0.001*****
	Pro information about hydrogen costs	0.565
	Pro information about hydrogen safety	0.530
Image	Fuel of the future	0.105
	Pro hydrogen concept	0.807
	Town gas experience	0.412
	Unpublicised status of hydrogen	**0.076***
	Negative social representation	0.626
Finance	Financial benefits	0.120
	Financial risks	**<0.001*****
	Conditional on financial implications	0.688
	Boiler rejection due to recent investment	0.533
Affect	**Positive emotions**	**0.083***
	Negative emotions	**0.065***
Environment	**Environmental benefits**	**<0.001*****
	Environmental risks	0.433
	Net-zero scepticism	0.583
	Conditional on environmental implications	0.199
Fairness and equity	**Choice deficit**	**0.012****
	Trust deficit	0.770
	Profit motives of energy companies	0.413
	Consumers shouldn't pay for the costs of the transition	0.199
	Government should pay	0.509
	Energy companies should pay	0.519
	Distributional injustice (general)	**0.044****

(*continued on next page*)

Table A1 (*continued*)

Core factor	Acceptance sub-factor	*p*-Value
Economy	***Economic benefits***	**<0.001*****
	Economic risks	0.319
	Energy security benefits	**0.051**
	Energy security risks	0.466
	Conditional on the cost-of-living crisis	**0.016****
Safety	***Safety benefits***	**0.061***
	Safety risks	0.129
	Conditional on safety implications	0.247
Logistics	Age barrier	0.466
	Disruptive impacts	**0.038****
	Logistical risks	0.240
Technology	Pro technology or modern progress	0.712
	Pro Research & Development for hydrogen	0.544
	Pro alternative low-carbon options (not hydrogen)	**0.021****
	Risk aversion to new technologies	**0.009*****
	Hydrogen perceived as an unproven technology	**0.027****
Performance	Efficiency or utility benefits	0.294
	Efficiency or utility losses	0.890
Social	Community benefits	0.274
	Societal benefits	0.096
	Societal risks	0.643
	Conditional on societal implications	**0.063***

The nine acceptance sub-factors discussed in Section 4.6 are highlighted in bold. Tertiary sub-factors explaining consumer heterogeneity are highlighted in bold italics.

*** Statistically significant at the 1 % level.

** Statistically significant at the 5 % level.

* Statistically significant at the 10 % level.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103401.

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