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Coupling green hydrogen production to community benefits: A pathway to social acceptance?

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ABSTRACT

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

1. Introduction

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

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Abbreviations: AVE, Average Variance Extracted; AWR, Awareness; BEIS, Department for Business, Energy & Industrial Strategy; CA, Cronbach Alpha; CB-SEM, Covariance based structural equation modelling; CCS, Carbon Capture and Storage; CMB, Common method bias; CR, Composite Reliability; CTA, Confirmatory Tetrad Analysis; CTAF, Comprehensive Technology Acceptance Framework; CVPAT, Cross-validated predictive ability test; DHA, Domestic Hydrogen Acceptance; DI, Disruptive Impacts; DHAM, Domestic Hydrogen Acceptance Model; DoI, Diffusion of Innovation Theory; EHB, European Hydrogen Backbone; EU, European Union; GDNOs, Gas Distributions Network Operators; GW, Gigawatt; HETs, Hydrogen energy technologies; HSE, Health and Safety Executive; HTMT, Heterotrait-monotrait; HFCVs, hydrogen fuel cell vehicles; IMPA, Importance-performance map analysis; IEA, International Energy Agency; KNW, Knowledge; MAE, Mean absolute error; MGA, Multigroup analysis; ML, Maximum likelihood; NE, Negative Emotions; Ofgem, Office of Gas and Electricity Markets; OLS, Ordinary least squares; PLS-SEM, Partial least squares structural equational modelling; PCB, Perceived Community Benefits; PSC, Perceived Socio-economic Costs; PE, Positive Emotions; PP, Production Perceptions; PAT, Public Attitudes Tracker; PT, Public Trust; RMSE, Root mean square error; R^2, Coefficient of determination; SEM, Structural equation modelling; SP, Safety Perceptions; SMR, Steam Methane Reformation; TAM, Technology Acceptance Model; TAS, Technology Affect Scale; TPB, Theory of Planned Behaviour; TWh, Terawatt hour; US, United States; UK, United Kingdom; UTAUT, Unified theory of Acceptance and Use of Technology; VIF, Variance inflation factor; 1G, First-generation; 2G, Second-generation.

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discounting that inhibits more immediate action.[1]

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

The potential role of hydrogen in combatting climate change is best reflected by the recent uptake of national (hydrogen) strategies [19–21], as described in Supplementary Note 1 (SN1). Of foremost relevance to this study, the UK government set an initial hydrogen production target of 5GW for 2030, following the release of its national Hydrogen Strategy in August 2021 [22]. However, following Russia's invasion of Ukraine, which has dramatically altered the global energy landscape,[2] the target has been doubled to 10GW[3] [23]. Specifically, the UK government suggests hydrogen could account for 20–35 % of UK final energy consumption (~250–460TWh) by 2050, in support of reaching the country's net-zero target [24]. Relatedly, Chapman et al. [25] suggest hydrogen could account for 2 % of global energy consumption under a scenario where 30 % hydrogen is blended into city gas.

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

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

Energy transition scholars posit that social acceptance [34,35] involves "multi-dimensional, dynamic processes" [36] which are "complex, multi-level, and polycentric" in nature [[37]:287]. Accordingly, social acceptance can be characterised as a multi-actor process [38] operating across the macro-, meso- and micro-levels [36]. Synthesising recent contributions to the literature [33,39–41], this study contends that consumer attitudes towards domestic hydrogen will involve a specific interplay between different acceptance dimensions and factors. On the one hand, deploying hydrogen homes will involve the 'human factor' in technology adoption [42],[5] which links strongly to attitudinal and behavioural acceptance at the household level [32,33]. At the same time, broader factors such as social trust and community benefits will influence public perceptions [41], as witnessed in the case of onshore wind siting [43].[6]

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

The DHAM is employed to determine the extent to which cognitive processes, social capital, environmental attitude, risk perception, cost-benefit appraisal, and affective response influence domestic hydrogen acceptance. The main motivation is to establish which constructs best predict support for hydrogen homes. Accordingly, the study develops a "theory-driven, data-grounded model" to advance understanding on sustainable energy acceptance [50]. In addition to advancing conceptual understanding, this analysis presents policy makers and key stakeholders with critical insights for realising national hydrogen economies and the wider energy transition.

Following this introduction, Section 2 provides an overview of theoretical and methodological developments in hydrogen acceptance studies, while Section 3 develops a series of hypotheses based on literature review findings. Next, Section 4 presents the conceptual framework, while Section 5 describes the methodology. Section 6 reports and discusses the results of the DHAM, while Section 7 concludes by highlighting the theoretical, empirical, and practical implications of the study.

2. Theoretical and methodological developments in hydrogen acceptance studies

Reviewing the early hydrogen futures literature [51,52], Ricci et al. [[53]:5878] concluded that conceptualisations of hydrogen energy technology (HET) acceptance overlook several "key aspects and dimensions by which people make sense of new technologies and consume them." Furthermore, survey studies on HET acceptance have been critiqued for lacking a whole-systems perspective, whereby focus on a specific end-use technology (i.e. hydrogen fuel cell vehicles and fuelling stations) neglects wider interactions across the hydrogen economy and energy system [53]. Subsequently, Roche et al. [54] called for acceptance studies to integrate a whole-systems perspective of HETs, while also advocating for expansion beyond frameworks rooted in social psychology,[7] risk perceptions, and economics.

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

Crucially, Scovell [39] laid the groundwork for systematically examining the relationship between socio-psychological factors and HET acceptance. Foremost, each of the 27 studies included in his review [39] operationalised the conceptual tenets presented in the

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[1] Jakimowicz [351] also discusses the energy transition as super wicked problem, when considered as part of a prosumer capitalism paradigm.

[2] In the aftermath of COVID-19 [168] and following the macro-economic shock of the ongoing Russia-Ukraine conflict [169,386], the geo-technological, economic, and political stakes of the global hydrogen economy are especially high for European nations [387], as further detailed in Supplementary Note 2.

[3] Of which at least 5GW should be sourced from electrolytic (i.e. 'green') hydrogen. Additionally, the Scottish Hydrogen Action Plan (December 2022) [130] aims for at least 25GW of installed renewable and low-carbon hydrogen production by 2045.

[4] The EHB envisions close to 40,000 km of hydrogen pipeline infrastructure across 21 countries by 2040 to support the decarbonisation agenda [26,27].

[5] Specifically, Lutzenhiser [42] discuss residential energy consumption as operating through macro-social and micro-behavioural processes.

[6] For example, Fournis and Fortin [43] describe cross-scalar interactions for deploying onshore wind farms, which span macro-economic, meso-political, and micro-social levels.

[7] i.e. models for attitude formation and behavioural intention.

Comprehensive Technology Acceptance Framework (CTAF)[8] and its predecessors [44] such as the Technology Acceptance Model (TAM) [55][9] and the Unified theory of Acceptance and Use of Technology (UTAUT) [56].[10] Notably, Venkatesh and colleagues [57] advanced a second iteration of the UTAUT (i.e. UTAUT2), before proposing a multilevel framework for analysing technology acceptance in the consumer context [58]. In parallel, researchers in the field of energy acceptance have adopted and adapted the TAM and UTAUT to examine a range of technologies [59–62], including smart meters and associated technologies for smart homes [63,64].

As summarised by Scovell [39], the CTAF synthesises well-established theories of human behaviour, namely the Theory of Planned Behaviour (TPB) [65], the Norm Activation Model (NAM) [66], and theories focused on risk perceptions [67] and related emotional responses to technology [68]. Through the lens of the CTAF, the following constructs were identified as salient factors of hydrogen acceptance: knowledge (objective and subjective); awareness; experience and engagement; perceived effects (risks, costs, and benefits); public trust; fairness; affect (i.e. emotional response); problem perception; personal norm; and socio-demographic factors [39].

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

While Lozano et al. [69] developed important comparative insights regarding public perceptions of domestic hydrogen and hydrogen for export in Australia, the analysis was limited to first generation multivariate regression analysis, which has significant limitations compared to SEM [70] (see Section 5.2). Despite the availability of advanced statistical methods for overcoming prior research limitations in quantitative studies, as specified by Scovell [39] and evidenced in Lozano et al. [69], recent contributions to the hydrogen acceptance literature have largely failed to leverage the benefits of second-generation techniques such as SEM [70,71].

Specifically, in 2022 Yap and McLellan [72] evaluated attitudes of Japanese society towards the hydrogen economy using an online survey.[11] The conceptual framework [72] drew on the earlier qualitative model of Schulte et al. [73] – albeit with a wider sense of coverage on knowledge, values, and related perceptions towards a future hydrogen-based economy[12] – but the analysis was limited to descriptive statistics. While this research decision may be partially attributed to the comparative focus, the analysis also reflects a persistent failure to operationalise acceptance constructs within hydrogen survey studies [39].

Researchers such as Emmerich et al. [74] and Scovell [39] acknowledge how individual, local, and general acceptance levels will shape prospects for developing national hydrogen economies [70]. More concretely, Gordon et al. [33] identified a range of social, political, economic, financial, contextual, ethical, socio-psychological, and socio-cultural factors [33]. This inherent multi-dimensionality reflects findings from other energy acceptance studies wherein a range of latent variables explain consumer attitudes [50,75,76]. This research internalises these dynamics by integrating a range of acceptance constructs to reflect the interplay between socio-political, community, market, and household acceptance dimensions [33,41], which are reflected in the hypotheses developed in Section 3 and subsequent conceptual framework (see Section 4).

Overall, this assessment of recent contributions to the literature supports the recommendation of Scovell [[39]:10455] to extend theoretical and empirical outputs on hydrogen perceptions, wherein a viable starting point is to examine how “different methods of production, storage and transport may interact to influence acceptance at different levels.” In response, analytical studies should reflect hydrogen’s unique status, as a technology with cross-cutting upstream and downstream impacts [39], which hold significant implications for shaping public perceptions and individual attitudes [32]. Critically, researchers should leverage the advantages of more rigorous quantitative methods such as PLS-SEM to advance comprehensive insights on domestic hydrogen acceptance (see Section 5.2).

3. Hypotheses development

This section reviews a range of literature materials to develop hypotheses for each of the exogenous constructs which compose the proposed model. Semantically, ‘exploratory’ research may suggest an explicit focus on hypothesis generation using qualitative methods [70,77]. Additionally, hypothesis testing may infer the need for an exclusively explanatory focus [78]. However, an exploratory approach also entails conducting quantitative research to test emerging hypotheses [70,77] under conditions of limited conceptual knowledge and scarce empirical [49]. In response, PLS-SEM provides a flexible (i.e. non-parametric) approach to support hypothesis testing and statistical conclusions via an exploratory, ‘causal-predictive’ research paradigm [49]. This research paradigm complements the ‘causal-explanatory’, retrospective focus of CB-SEM [79], as further discussed in Section 5.2. As a result, PLS-SEM has proved the method of choice for social scientists when conducting exploratory modelling and hypothesis testing across a range of disciplines [80–82] including sustainable energy transitions research [83–87]. In total, ten hypotheses are proposed to test the antecedents of domestic hydrogen acceptance and determine the predictive capabilities of the DHAM (see Section 6.5).

3.1. Awareness and knowledge

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

Currently, hydrogen appliances for domestic heating and cooking [89] remain at the formative phase [90] or pre-deployment stage of technology diffusion [91,92]. Consequently, few consumers are yet to

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[8] Also referred to in the literature as the Sustainable Energy Acceptance Technology (SETA) model.

[9] The TAM was developed by Fred Davis in the mid-1980s [388], integrating constructs from the Theory of Reasoned Action (TRA) [389], as well as Rogers’ Diffusion of Innovation (DoI) theory [390], to evaluate user acceptance of computer technologies in the organisational setting [391].

[10] In 2001, Venkatesh et al. [56] subsumed a range of critical acceptance constructs from eight established models to develop the UTAUT framework.

[11] The authors conducted a nationally representative online survey ($N = 2880$) in March 2022 [72], which was compared to results from 2015 ($N = 3133$) [97].

[12] i.e. self-reported and objective knowledge and values towards the environment, energy security, safety, economic efficiency and energy justice.

[13] Awareness-knowledge is a proxy for familiarity with a given technology, which is a prerequisite for subsequent knowledge types and technology adoption [392,393]. Thus, awareness influences the scope for socio-psychological and attitudinal responses towards a given technology [209].

trial hydrogen home appliances [93,94]. Thus, little information is known about consumer attitudes towards potential adoption [32], as well as underlying social acceptance [33,69]. Given the nascency of the low-carbon hydrogen industry, this study reports survey responses regarding awareness and subjective (i.e. self-rated) knowledge [95].[14]

Foremost, hydrogen awareness and knowledge levels remain low across most countries [96–98] including the UK [99]. Notably, awareness of hydrogen boilers is significantly lower than other low-carbon heating technologies such as solar thermal panels and heat pumps [100], underscoring the peripheral status of domestic hydrogen [101,102]. Nevertheless, consumer attitudes towards HETs often side towards the positive end of the acceptance spectrum [33,103], while knowledge and awareness of renewable energy typically increases support for hydrogen [104]. This positive association is particularly prevalent among educated males [105–107].

Given the current evidence base, this study tests the following hypotheses wherein a positive association[15] is posited between cognitive processes and domestic hydrogen acceptance in relation to awareness and subjective knowledge[16] (see SN3):

H1. Awareness (AWR) of low-carbon energy technologies including hydrogen home appliances will positively influence the social acceptance of domestic hydrogen.

H2. Knowledge (KNW) about hydrogen fuel will positively influence the social acceptance of domestic hydrogen.

3.2. *Public trust*

Public trust is a multi-dimensional construct, which reflects how society perceives the competence and integrity levels of given stakeholders [108–110]. Public trust has important implications for community acceptance [34], with evidence from China (Jiangsu Province) highlighting how community backing for industrial agglomeration (i.e. synergies between local industries and manufacturers) can promote support for the hydrogen economy [111].[17] Trust dynamics have been shown to heavily shape hydrogen acceptance at the individual, community, and national level [112], reinforcing the multi-dimensional focus embedded in the 'five dimensions of domestic hydrogen acceptance framework' [33].

Following such projects, extant evidence supports the notion that public trust is a key dimension of domestic hydrogen acceptance [32,93,113], especially given the community and individual impacts of converting the gas grid [39,114]. Crucially, a deficit in public trust [41] may undermine socio-political acceptance [34], thereby aggravating the potential for social friction towards the hydrogen economy [115].

UK consumers have comparatively high levels of trust in evidence on hydrogen provided by the Health and Safety Executive (HSE), whereas the media are regarded as untrustworthy [113]. Interestingly, another study reported neutral levels of trust in the national regulator, the Office of Gas and Electricity Markets (Ofgem) [116]. Furthermore, the public may have relatively high confidence regarding the ability of government and industry to carry out requisite safety and environmental checks [113,117], but question the commitment of the same entities towards enacting procedural and distributional justice [41,118].

The public may also look towards renewable energy producers to steer the hydrogen transition in the right direction [69,119] by ensuring the green credentials of national hydrogen strategies come to fruition [120]. Relatedly, financial institutions are actively involved in supporting the transition to a low-carbon economy [121], although significant financial and policy de-risking is needed to dimmish green investment risks [122]. Accounting for these dynamics, this study measures public trust in the following actors and stakeholders: the media, Ofgem, Gas Distributions Network Operators (GDNOs), renewable energy producers, and financial institutions (see SN3).

In summary, public trust can drive support for residential decarbonisation [123], positively shape attitudes towards climate change and environmental policies [124,125], and act as a mechanism for raising social capital and improving economic efficiency [126]. In response, the following hypothesis is formulated to test the effect of public trust on domestic hydrogen acceptance (see SN4):

H3. Public Trust (PT) in key actors and stakeholders will positively influence the social acceptance of domestic hydrogen.

3.3. *Production perceptions*

The relative merits of different hydrogen production technologies have been discussed in view of techno-economic factors [31,127] including the levelised cost of CO_2 mitigation [128]. In parallel, prospects for respective hydrogen production pathways will hinge on public perceptions [119,129]. For example, Parkison et al. [128] and Griffiths et al. [7] note the likely challenge associated with nuclear-based hydrogen production in view of negative safety perceptions and lack of public support.

The UK Hydrogen Strategy envisions a 'twin-track' production approach reliant on steam methane reformation (SMR) and carbon capture and storage (CCS), alongside "electrolytic hydrogen predominantly powered by renewables" [[22]:30]. More ambitious targets for hydrogen production since the outbreak of the Russia-Ukraine conflict [23,130] (see SN2) signal the importance of hydrogen production pathways as a key pillar of national energy policy, with key implications for social acceptance [129].

The 'hydrogen futures' literature [51,131] demonstrates a stronger degree of public support for renewable energy-based production [99,119,132], compared to a blue hydrogen production (i.e. SMR with CCS[18]) [106,117]. The Welsh public expressed a preference for hydrogen production generated by wind farms as opposed to fossil fuel feedstocks [107]. Similarly, Norwegian citizens showed support for coupling onshore wind and hydrogen production [133], alongside a clear preference for green hydrogen over alternative options [119].

However, data collected by Yap and McLellan [72] highlighted two divergent perspectives among Japanese respondents: 55 % preferred cheaper 'grey' hydrogen production (i.e. fossil-fuel based without CCS), whereas 45 % were in favour of green hydrogen, given its environmental benefits and despite its higher costs. Interestingly, findings from online focus groups conducted in the UK suggest a lack of clarity regarding the premise of the government's twin-track approach, with environmentally engaged respondents expressing higher degrees of scepticism [129].

It follows that the 'colour labels' [134,135] of hydrogen production methods communicate environmental cues to citizens, thereby shaping social acceptance [119]. Accounting for the foreseeable influence of hydrogen production pathways, and by proxy environmental attitudes towards these decisions, the following hypothesis is proposed in view of

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[14] The rationale applied is that subjective knowledge (hereafter 'knowledge') can also be considered as a close proxy for awareness-knowledge [88] or perceived familiarity [393], and may ultimately reflect one's potential interest and engagement level [263,392].

[15] While simplified within this research model and examined as a direct antecedent of acceptance, knowledge is nonetheless recognised as a multi-dimensional construct [394], which has scope to influence one's behavioural response in several ways [209] through multiple mechanisms [395].

[16] Specifically, respondents were asked: "How much do you know about hydrogen fuel?"

[17] By no coincidence, the German Government's National Innovation Programme for Hydrogen and Fuel Cell Technology [396] was supported by academic projects resonating with the notion of public trust, namely, HyTrust (2009–2013) and HyTrustPlus (2014–2016).

[18] Notably, CCS presents its own set of unique challenges related to social acceptance [180,397,398].

the twin-track approach (see SN3), wherein the effect may prove positive or negative according to the sample composition:

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

3.4. Safety perceptions

Blending hydrogen into the natural gas grid [136,137] may present a tangible measure towards realising national hydrogen economies [138,139]. However, this pathway and related infrastructure investments such as hydrogen-dedicated pipelines [26] will incur new safety challenges [140,141]. Potential safety risks will be heightened when considering hydrogen for domestic use [31] as opposed to industrial applications [7].

Notably, examining acceptance for HFSs in Japan, Ono and Tsunemi [142] found that risk perception factors related to safety incidents were stronger predictors of consumer acceptance than psychological and socio-demographic variables. Prior research has also shown that hydrogen's distinct physical and chemical characteristics may elicit consumer concerns [89], and moreover, feelings of fear and dread [142,143].

Both UK [93,144] and Australian survey respondents [69,145] expressed concerns over hydrogen's colourless flame and lack of smell, as well as its combustibility and flammability [32]. Interestingly, female respondents in Australia reported higher concerns than males in view of hydrogen's potentially disruptive impacts to the lived experience of cooking and associated risk factors [106]. By contrast, an earlier study in the Netherlands observed stronger perceptions of explosiveness among males [105]. Similarly, in the case of green hydrogen production, Welsh respondents raised concerns over explosive risks [144].

It follows that safety perceptions may play an important role in shaping hydrogen acceptance, especially during the early stage of the transition where risks are likely to be most elevated and uncertain. Nevertheless, online survey ($N = 700$) and paper-based survey respondents ($N = 102$) from the North of England perceived potential safety benefits from a switch to domestic hydrogen [102].[19] Focus group results also suggest that citizens feel relatively reassured about hydrogen, provided adequate safety tests are carried out [93]. However, the safety risks of hydrogen cooking are perceived to be higher than for hydrogen heating [89,146].

In view of the notion that risk perceptions may stem largely from media coverage [147,148], and given the current lack of consensus on safety perceptions within the literature, this study focuses on a comparative assessment between hydrogen and natural gas (see SN3), without specifying the nature of this relationship [149]. Accordingly, the following hypothesis is developed to advance the evidence base, while seeking to mitigate perception bias:

H5. Safety Perceptions (SP) will significantly influence the social acceptance of domestic hydrogen.

3.5. Perceived disruptive impacts

It is widely accepted that converting the gas grid to hydrogen will engender a certain level of safety challenges [150,151], which may translate to perceived risks in the eyes of the public [89,94]. To date, most of the literature has concentrated on risk perceptions concerning safety aspects [73,152,153]. Safety-related concerns can be classified as 'hard' risks concerning technical hazards related to pipelines [154] and appliances [155], wherein the dangers are severe and carry direct implications for human wellbeing [156].

By contrast, 'soft' risks are less harmful and easier to mitigate [44,156]; revolving around potential short-term disruption risks which households may incur during the hydrogen switchover [93]. These non-hazardous risks [156] can be measured according to levels of consumer concern or worry [157]. For example, one nationally representative online study conducted in the UK ($N = 1027$) found that 20 % of respondents were cautious about adopting domestic hydrogen and concerned about disruptive impacts [158].

Risk perceptions in this sense will revolve around potential disruptive impacts, which may include "infrastructural changes and operational activities at street level, as well as temporary disconnection from the gas grid and engineering activities within properties" [[33]:18]. Focus group participants from one UK study specified a general tolerance for disconnection from the gas grid for a maximum of four days [93], which has been corroborated by subsequent findings [41]. However, thresholds for the duration of disconnection may prove context specific and depend on energy vulnerabilities [41,93].

Elsewhere, focus group participants have described disruptive risks in terms of higher levels of traffic and noise [41], which links to the perceived burden of appliance installation (i.e. hydrogen boilers and hobs) [93]. Critically, to enable conditions for a large-scale conversion program [159], consumers must perceive disruption-related risks to be tolerable [33]. Accordingly, the following hypothesis is explored to account for prospective short-term disruptions (see SN3), which if not adequately mitigated could impede the prospective transition to hydrogen homes:

H6. The Perceived Disruptive Impacts (PDI) of the hydrogen switchover will negatively influence the social acceptance of domestic hydrogen.

3.6. Perceived socio-economic costs

The perceived socio-economic costs of domestic hydrogen can be measured at different scales [33] including the macro- or national level [36]. However, this construct remains underexplored by researchers [39,160], with limited theoretical or empirical investigation beyond the boundaries of safety and environmental impacts [39], which is also reflected in the wider technology acceptance literature [161]. In most instances, discussions on cost-related aspects of hydrogen are restricted to the individual unit of analysis regarding financial impacts to consumers [102,162,163], and sometimes extended to the community level by considering negative effects to host communities [164].

While the existing evidence base in sparse, some notable results have been reported in the literature. Foremost, Scott and Powells [102] found that most survey respondents in the North of England anticipated neutral or positive macro-economic impacts from the domestic hydrogen transition. However, it should be noted that the distribution of responses was skewed towards neutral perceptions (i.e. 'no impact on the economy') [102]. Furthermore, it should be borne in mind that the survey in question [102] was conducted before a string of unpredictable and destabilising economic events [165,166], following the COVID-19 pandemic [167,168] and Russo-Ukrainian War [169,170], as described in SN2. Consequently, the current political and economic landscape remains volatile [171,172], with concurrent events exacerbating fuel poverty pressures in the UK [173,174].

Drawing from previous research [32,44], this study focuses on the macro-economic risks of the domestic hydrogen transition, which will influence both socio-political and market acceptance. Two related areas of interest receive attention, namely, the perceived impacts of the hydrogen switchover on energy insecurity and fuel poverty (see SN3). These areas also serve as proxies to inform consumer perceptions regarding the cost-competitiveness and affordability of domestic hydrogen. Reflecting these measurements items, the following hypothesis is tested:

H7. The Perceived Socio-economic Costs (PSC) of transitioning to

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[19] 17.3 % and 34.7 % answered positively while 13.9 % and 7.9 % answered negatively, although neutral (i.e. no impact) was the prevailing response (i.e. 68.9 % and 57.4 %).

hydrogen homes will negatively influence the social acceptance of domestic hydrogen.

3.7. Perceived community benefits

Perceived risks and social costs are often critical to energy acceptance, especially when concerning a hazardous technology such as nuclear power [175,176], as well as emerging energy technologies [177]. Nevertheless, recent evidence suggests that perceived benefits is the most influential predictor of social acceptance; not only for renewable electricity generation [178] and low-carbon heating technologies [179], but also CCS [180] and even nuclear power [181,182].

As with perceived risks and social costs, perceived benefits can be evaluated across different dimensions [183,184]. For example, Damette et al. [185] investigated consumer perceptions in relation to hydrogen's benefits for French households, the electricity grid, and environment. Notably, survey respondents in both Australia [106] and the UK [117] express support for implementing a local green hydrogen economy aligned to community benefits; identified as job security, energy security, and environmental improvements [186], which may help reinvigorate industrial communities [41,117]. Furthermore, support for hydrogen in the North of England also increased when participants were briefed about the fuel's potential environmental benefits [113], while Bentsen et al. [119] reported perceived environmental benefits as a key predictor of hydrogen acceptance in Norway.

Given the importance of local economic, social, and environmental benefits to energy technology acceptance [187], these parameters are likely to shape public opinion and consumer attitudes towards domestic hydrogen [32]. While awareness regarding the benefits of hydrogen remains relatively low [39,188], unpacking this tripartite dimension (see SN3) may reveal key inferences regarding hydrogen's perceived contribution towards tackling the energy trilemma [189] and safeguarding against energy injustice [190]. Consequently, the following hypothesis is examined to account for the remaining dimension of 'perceived effects' [39,191]:

H8. The Perceived Community Benefits (PCB) of transitioning to hydrogen homes will positively influence the social acceptance of domestic hydrogen.

3.8. Positive and negative emotions

Socio-psychological and attitudinal drivers find further expression in the form of emotional responses [192,193], which is reflected in the academic literature via the application of various psychological evaluation metrics [161,194,195] such as the Technology Affect Scale (TAS) [196]. Mirroring findings in the information technology acceptance literature [197,198], emotions play an instrumental role in shaping energy acceptance [199,200]. The affective (i.e. emotional) dimension of renewable energy acceptance has attracted increasing attention from researchers [200–203] when examining the broader potential for a sustainable energy transition [193,204].

Qualitative findings from this dataset cite a wide range of emotional responses, with optimism, hopefulness, happiness, excitement, and eagerness among the most prevalent responses, while concern, confusion, fear, nervousness, and scepticism dominated negative reactions [103,118]. Negative emotions may prove particularly relevant for risk perceptions related to safety aspects [205,206]; foremost when consumers associate hydrogen with explosiveness, danger, and catastrophe vis-à-vis past incidents [107,147,205,207]. Emotions such as fear and dread [142,143,208] could shape the emerging contours of hydrogen acceptance, as witnessed historically with controversial energy technologies such as nuclear power [209]. Additionally, feelings of unfamiliarity concerning hydrogen may evoke anxiety, concern, and scepticism [54,102].

Conversely, positive emotions such as pride, joy, and gratitude may prove emergent among local hydrogen communities [208,210], reinforcing the imperative to examine the emotional dimensions of energy acceptance through a holistic lens [208]. It follows that positive and negative emotions should be evaluated as interacting, yet distinct dimensions of hydrogen acceptance [44]. As a result, this study investigates the following hypotheses in parallel (see SN3):

H9. Positive Emotions (PE) towards hydrogen homes will positively influence the social acceptance of domestic hydrogen.

H10. Negative Emotions (NE) towards hydrogen homes will negatively influence the social acceptance of domestic hydrogen.

4. Conceptual framework

The hypotheses generated in Section 3 and associated constructs provide the foundations for advancing an integrated theory of domestic hydrogen acceptance,[20] which incorporates six specific dimensions as illustrated in Fig. 1: cognitive processes, social capital, environmental attitude, risk perceptions, cost-benefit appraisal, and affective response. Through this approach, the study engages with multiple acceptance dimensions, as opposed to a more limited set of psychological parameters [39,69] and attitudinal factors [89,102]. While each exogenous construct can be classified as a socio-psychological factor under a traditional technology acceptance framework lens [46,69], each unique aspect characterises the multi-dimensional nature of the DHAM.

As foundational drivers of attitudes and behaviours [211], awareness and knowledge represent key **cognitive processes** which shape domestic hydrogen acceptance [74], corresponding to H1 and H2 in the proposed model [74]. By contrast, public trust develops via social and cognitive processes [212,213], which enable individuals to form expectations about scenarios and relationships [214] to better evaluate new social settings and choices [212]. Moreover, trust is a critical aspect of **social capital**, which may encourage community acceptance and cohesion, alongside local economic development [215], in support of deploying and scaling up hydrogen homes [31], as explored via H3.

As described, production perceptions can be conceptualised as a proxy for **environmental attitudes**, since UK households may distinguish between support levels for renewable-based and non-renewable based hydrogen production pathways [129], which motivates H4. Although hydrogen production pathways entail important consequences for energy security and other macro-economic factors such as job creation [31,164], the environmental focus typically pervades the public discourse. Specifically, the climate change credentials of blue hydrogen remain highly contested by the scientific community [216,217], while national hydrogen strategies have also been criticised for lacking green commitments, characterised by a "scale first and clean later" ethos [120].

At the level of **risk perceptions**, safety-related impacts and disruptive impacts can be linked to 'hard' and 'soft' risks, respectively [44]. Hard risks correspond to hazards involving damage to infrastructure (i.e. pipeline-related incidents and gas leakage) or end-user accidents (e.g. fire event triggered by a hydrogen cooker), which pose a threat to the environment and compromise human safety [154,156], as explored in H5. By contrast, soft risks are associated with concerns and worries over non-hazardous events [156], such as street-level disruption and other short-term impacts incurred during the hydrogen conversion process [41,93], which are focused on in H6.

Researchers typically focus on the perceived benefits of domestic energy technologies when conducting quantitative studies, while perceived costs are often overlooked [44]. This pattern holds true in the hydrogen acceptance literature [39], although the disparity between

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[20] Notably, Brosch et al. [192] demonstrated the increased explanatory power of behavioural models which integrate appraisal-emotion constructs to predict energy-related decision-making at the micro-scale.

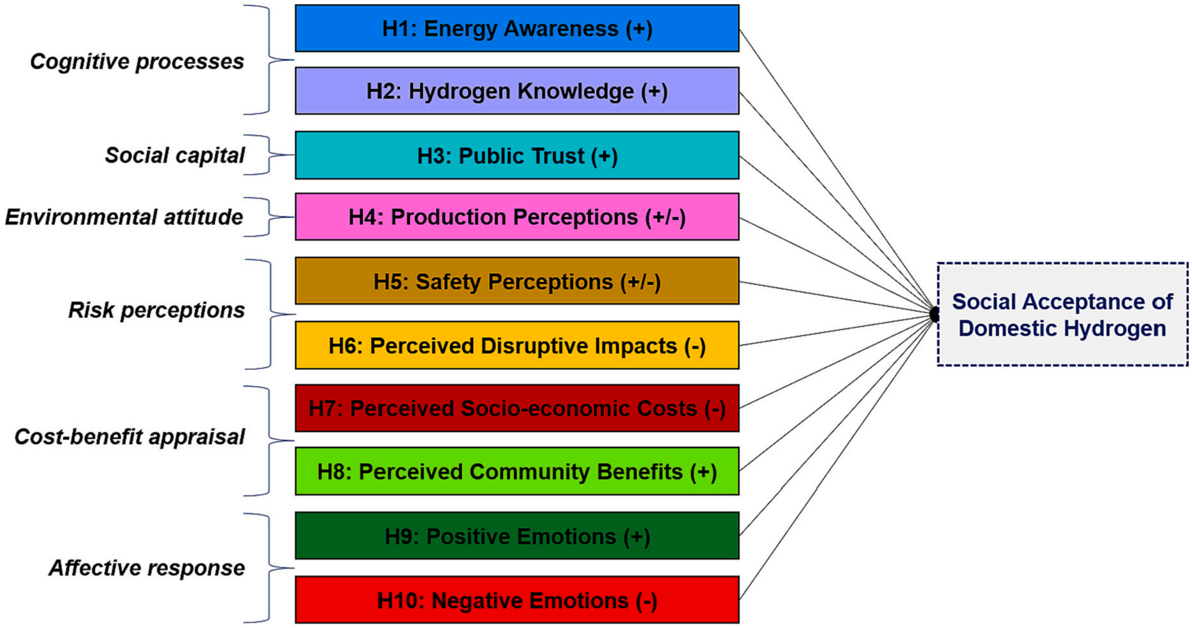

Fig. 1. Conceptual framework for examining the social acceptance of domestic hydrogen.

assessing these two constructs is somewhat less pronounced [44]. In response, this study subsumes perceived socio-economic costs and perceived community benefits [218,219] under the dimension of **cost-benefit appraisal** [220].[21]

As a result, this framing integrates measures of both socio-political and community acceptance [33] vis-à-vis negative (i.e. perceived socio-economic costs) and positive implications (i.e. perceived community benefits) of hydrogen homes, which are tested in H7 and H8 respectively. In doing so, this analysis also provides a means for directly comparing public perceptions across the macro- and meso-level.[22]

Lastly, socio-psychological and attitudinal drivers find further expression in the form of **affective response** [192,193], which motivates H9 and H10. Critically, intuitive feelings will influence social acceptance when information remains relatively limited or without a clear consensus, and risk-benefit judgments cannot be arrived to easily [38], which is the case for an emerging technology such as domestic hydrogen. Accordingly, emotional responses to the domestic hydrogen transition may reflect underlying cognitive processes, social and cognitive interactions, environmental attitudes, risk perceptions, and related cost-benefit appraisals, leading to the conceptual framework illustrated in Fig. 1.

5. Material and methods

5.1. Survey design and data collection

This quantitative study employed a web-based survey to collect data on consumer attitudes towards domestic hydrogen in the UK. The survey design was derived through literature review [31–33] and qualitative results from online focus groups [41,129,146]. Questionnaire items were further developed following inputs from hydrogen experts and social scientists working in the energy transitions field.

After programming the survey in Qualtrics [221], content and face validity were established through a series of internal piloting rounds. Following an iterative process of survey development which spanned several months, the final questionnaire was deployed by a market research company.[23] Supplementary Note 3 (see SN3) provides details of the questionnaire items, answer scales, and literature which informed the survey design.

The sample is composed of four specific consumer segments (see SN5) which serves three key functions: (1) enabling opportunities for multigroup analysis (MGA) which has been leveraged in follow-up work [222]; (2) ensuring a spectrum of consumer profiles are represented in the sample through inclusion of participants with different levels of technology knowledge and interest, environmental engagement, and socio-economic status (i.e. fuel stressed and non-fuel stressed respondents); and (3) increasing national representativeness through this design, for example, by directly accounting for the increasing prevalence of fuel poverty pressures in the UK [173,223].

The study was strengthened by implementing a series of measures (i.e. filters and quotas) to approximate a broadly nationally representative sample (see SN5). As demonstrated in other research fields such as psychology [224], epidemiology [225], and health services research [226], national representativeness enables clearer estimation of country wide patterns to support generalisable conclusions. Importantly, domestic hydrogen acceptance studies conducted in the UK [113] and Australia [69] have adhered to representing the national population, which is also the aim of this research.[24]

Importantly, this study engages exclusively with existing users of gas boilers and hobs. Furthermore, two additional filters were employed to support the objective of engaging with respondents more likely to be actively involved with a prospective transition to hydrogen homes, or other low-carbon domestic energy technologies: (1) at least moderate involvement in decision-making around the purchase of their heating and cooking appliances; and (2) at least moderate importance attributed

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[21] The underlying logic is that consumer attitudes towards perceived socio-economic costs at the macro-level (i.e. fuel poverty and energy security impacts) and perceived community benefits (i.e. economic, social, and environmental) will contribute towards a cost-benefit analysis of domestic hydrogen.

[22] A more robust representation would be afforded by including a third measure of perceived costs, namely, (perceived) negative environmental impacts. The survey instrument employed for this measure (PC3) failed to load on the construct, as further discussed in Section 7.2.

[23] The survey ran from October 6th to December 23rd, 2022, and was monitored daily by the lead author.

[24] Specifically, quotas were applied for the following socio-demographic variables: age, gender, housing tenure, housing type and location.

to being able to choose these appliances.[25] Notably, the research design supported a valuable opportunity to compare safety perceptions of natural gas and hydrogen for deeper contextual understanding (see Section 3.4). Overall, a broadly national representative survey sample was secured ($N = 1845$), albeit with room for improvement around variables such as age and housing tenure in subsequent studies (see Table A1).

5.2. *Structural equation modelling: a second-generation statistical technique*

Structural equation modelling (SEM) has a rich and well-documented history [227–229], characterised as a second-generation (2G) statistical technique which is superior to first-generation (1G) techniques for modelling complex causal relationships between latent and observed variables [70,230]. Larsson et al. [231] describe regression as engaged with predictive analysis irrespective of causal mechanisms, whereas SEM, through its path modelling approach, is rooted in hypotheses about causal processes:

> "Path modelling is the application of statistical modelling to datasets with the objective of testing and explaining causal hypotheses about theoretical measurement models and structural paths" [77].

In a standard regression model, each equation implies "a statistical relationship based on a conditional expected value."[26] By contrast, SEM implies a 'functional relationship' which is expressed through a corresponding conceptual model, path diagram, and mathematical equations [232]. Put differently, within a SEM, each equation represents a causal link as opposed to an empirical association [233], enabling researchers to examine the causal networks underlying real-world relationships in a more comprehensive way compared to correlation-based models [234].

Accordingly, SEM offers several advantages compared to multivariate regression analysis: supporting theory development through simultaneous testing of complex relationships (i.e. measurement and structural models);[27]; incorporating measurement error and unexplained variance in the modelling parameters; and ability to link micro- and macro-perspectives of complex phenomenon [234,235]. Compared to 1G techniques, SEM supports greater statistical power [236],[28] higher levels of flexibility (i.e. methodological versatility) [231], ability to test a priori hypotheses about causal relationships [231,237], alongside "big-picture, model-based reasoning," whereby relationships between variables are conceptualised as part of an overarching explanatory system processes [231].

5.2.1. *Approaches to structural equation modelling: CB-SEM and PLS-SEM*

CB-SEM and PLS-SEM present complementary, yet distinctive, statistical approaches for estimating parameters of theoretical models [238,239]; diverging in terms of measurement philosophies, estimation procedures, and statistical outcomes [240], as summarised in Table A4. Notably, the application of PLS-SEM in the social sciences has grown exponentially within the last two decades [77], with scholars increasingly disseminating the predictive benefits of the method to the research community [79,241,242]. Nevertheless, selecting the most suitable SEM approach remains of a focal point of academic debate [80,243], emphasising the need for clear research justification.

As a confirmatory technique, CB-SEM determines whether the hypothesised model fits the observed sample data [77,238,244]. With a focus on model fit and stronger data requirements, CB-SEM is the optimal approach for testing an established and concise theoretical model such as the Theory of Planned Behaviour (TPB) [245,246]. Thus, researchers may adopt CB-SEM for purposes of theory confirmation [80,247], as applied by Gölz & Wedderhoff [212] when examining onshore wind acceptance in Germany.

CB-SEM follows a maximum likelihood (ML) estimation procedure [248], treating constructs as common factors to explain the covariation between associated indicators [247]. The common factor approach splits total variance into common, unique, and error variance but only uses common variance for estimating the model [249,250]. Thus, residual variance is excluded as measurement error and the focus is on estimating the proportion of common variance explained [250]. As a result, the CB-SEM approach is more prone to metrological uncertainty,[29] which may compromise the validity of the measurement model [249].

In response, the CB-SEM approach may motivate researchers to reduce the number of indicators per construct to increase model fit [239], which has adverse consequences on metrological uncertainty and associated validity [249]. CB-SEM is also subject to factor (score) indeterminacy, since there are infinite sets of latent variable scores that can fit the model to the same extent [70,249]. Therefore, correlations between a common factor and variables external to the factor model become indeterminate, which renders CB-SEM ill-suited for purposes of prediction [70,249].

Overcoming this limitation and bridging the gap between explanation and prediction [251],[30] PLS-SEM produces a unique (i.e. determinate) score for each composite per observation following calculation of indicator weights and loadings, which serve as proxies for the latent constructs [249]. These proxies serve as inputs for executing ordinary least squares (OLS) regression[31] to minimise the error terms (i.e. residual variance) of each endogenous construct in the model [249]. Consequently, PLS-SEM employs a composite-based measurement philosophy; reflecting the notion that latent constructs can be estimated by linearly combining indicators for each construct [249,252].[32] Notably, the composite-based approach supports handling of more complex data compared to CB-SEM [252].

Thus, as a variance-based approach [238], PLS-SEM estimates path coefficients to maximise the explained variance (R^2) of a target construct [249] within a conceptually-grounded path model [253], whereas CB-SEM is limited to explaining the covariation between indicators in the measurement and structural models. Unlike CB-SEM, PLS adopts the logic the entirety of an indicators' variance is relevant for estimating path models [249]. Guenther and colleagues [250] emphasise this distinction as a motivating reason to utilise PLS-SEM, since residual variance may contribute towards theoretical or empirical meaning due to interaction effects between indicators and constructs.

When extending frameworks such as the TPB [254–256] or modelling complexity via an integrated technology acceptance model (TAM) [257–259], researchers can employ PLS-SEM for purposes of theory development [255]. Accordingly, PLS-SEM is recommended in situations of high complexity where limited theory formation has been

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[25] Both questions were measured using a five-point Likert scale where the moderate response represented the mid-point.

[26] i.e. each equation within a regression model represents "the conditional mean of a dependent variable as a function of explanatory variables" [230]. Alternatively, Larsson et al. [231]describe regression "as specifying a conditional mean of the outcome based on the predictors."

[27] By contrast, 1G statistical techniques require separate analyses to perform validity and reliability tests, which lack a direct relationship to formal hypothesis testing and as a result cannot provide overall fit indices [399].

[28] i.e. Probability of rejecting a false null hypothesis [236]

[29] i.e. the dispersion of measurement values that can be explained by the object or concept under examination [249].

[30] PLS-SEM can test a model's predictive capabilities by drawing on out-of-sample tests, but is also suitable for explanatory modelling as supported by in-sample predictive tests [251,400].

[31] OLS minimises the sum of the squared differences between the observed and predicted values of the dependent variable [77].

[32] i.e. PLS-SEM obtains parameter estimates via repeated least squares regression with a single dependent variable [252].

established [80,260], as reflected in the case of emerging hydrogen energy technologies [163,261–263]. Nevertheless, it should also be noted that PLS-SEM is suitable for conducting confirmatory research [49,264].

In summary, SEM practitioners such as Henseler [238] and Hair et al. [249] characterise PLS-SEM as a 'causal-predictive' paradigm with the goal of testing a model's predictive power based on theory and logic, whereas CB-SEM follows a 'causal-explanatory' paradigm predicated on theory confirmation and model fit. As a result, PLS-SEM bridges the gap between CB-SEM and exclusively predictive methods [251] such as machine learning and artificial neural networks [265–268].

5.2.2. *Application of PLS-SEM in SmartPLS 4.0*

Using SmartPLS 4.0 software [269], the two-stage approach was applied to analyse and interpret the survey data, firstly assessing the measurement model and secondly, evaluating the structural model. Beforehand, several measures were required to justify the use of PLS-SEM [270], such as a valid research design and sufficient sample size [236], which were checked using model model-specific estimates [271]. Employing G*Power software (see SN6), the proposed model can demonstrate small effect sizes of 0.02 at a 95 % significance level ($\rho \leq 0.05$) for the specified sample ($N = 1845$). Secondly, skewness and kurtosis tests were conducted to assess normality [49,272], which confirmed all values were within the preferred threshold of ±1 (see SN7). Thirdly, common method bias (CMB) was ruled out, since Harman's single factor test [273] returned an overall variance of 29.5 %, well below the threshold of 50 % (see SN7). Overall, the preliminary assessment confirmed the integrity of the data and the suitability of using PLS-SEM.

6. Results and discussion

This section reports and discusses the results in four stages. Firstly, Section 6.1 reports descriptive findings for the constructs operationalised in the DHAM, as measured using two respective Likert scales in the online survey (see SN3). In doing so, the first sub-section frames the PLS-SEM analysis and hypotheses results against observations at the indicator level. Next, 6.2 proceeds by assessing the measurement model. Thereafter, Section 6.3 assesses the structural model; as supported by including an IMPA in Section 6.4. Section 6.5.1 reports the in-sample and out-of-sample predictive power of the DHAM. Finally, Section 6.6 concludes by discussing the links between acceptance dimensions and constructs.

6.1. *Descriptive statistics*

The analysis of descriptive statistics highlights several findings, which hold important implications for the configuration of domestic hydrogen acceptance. Firstly, in relation to the cognitive dimension, this study finds that awareness and subjective knowledge of hydrogen remain low (see Table 1), which is consistent with recent findings in the literature [96,119]. For example, based on data collected in the Spring of 2022 ($N = 4372$), the UK government found awareness of hydrogen fuel ($M = 2.44$, $SD = 1.11$), and of its potential future uses to reduce emissions ($M = 2.34$; $SD = 1.09$) to be relatively low when measured on a five-point Likert scale [274].

Secondly, in respect to social capital, it emerges that trust in the media is lowest while trust in financial institutions also falls below the mean (see Table 1). This result reflects a pronounced trust deficit in the media [106,113], signalling a growing perception that some areas of journalism are increasingly entrenched in perpetuating a cycle of distrust and misinformation [275]. Although financial institutions have a critical role to play in securing a low-carbon economy [122,276], respondents doubt their capabilities and commitments towards steering the hydrogen transition. Supporting this observation, globally retrieved survey data such as the Edelman Trust Barometer has highlighted a

Table 1
Summary of results from online survey questions on domestic hydrogen acceptance.

Acceptance dimension and construct(s)	Results at the construct level	Key findings and implications
Cognitive processes		
Awareness (AWR)	- AWR returned a mean score of 2.00 ($SD = 0.99$) as measured on a 5-point scale (1–5) - The descriptive results also indicated a pronounced lack of awareness regarding the UK Hydrogen Strategy ($M = 1.69$; $SD = 1.00$)[a] - Minimal difference between the two measures of AWR ($SD = 0.07$)	- Consistent with previous studies [69,99], awareness (and knowledge) is considerably low, confirming that the notion of 'hydrogen homes' is yet to penetrate the public consciousness
Knowledge (KNW)	- KNW returned a mean score of 1.96 ($SD = 2.16$) as measured on a 5-point scale	- Subjective knowledge of hydrogen exhibits a considerably higher level of variance than hydrogen awareness, inferring that exposure to information is comparatively more similar than perceived levels of understanding
Social Capital		
Public Trust (PT)	- PT returned a mean score of 5.10 ($SD = 2.41$) as measured on an 11-point scale (0–10) - Moderate difference between the five measures of PT ($SD = 0.68$)	- Variability among public trust indicators suggests more public confidence in the actions of the renewable energy sector for supporting a cost-effective, efficient, and fair transition to hydrogen homes - Trust levels in Ofgem and GDNOs is relatively comparable, implying similar attitudes towards the energy regulator and companies managing the UK gas distribution network
Environmental attitude		
Production Perceptions	- PP returned a mean score of 6.35 ($SD = 1.93$) as measured on an 11-point scale - Moderate difference between the five measures of PP ($SD = 0.72$) - The strongest preference is for an immediate focus on supporting green hydrogen production (PP3, i.e. before 2030) - Blue hydrogen production is more strongly supported as a long-term pathway (PP2) compared to a solution for the current decade (PP1)	- To a degree, the survey results imply the potential undermining of the twin-track approach in terms of socio-political acceptance [33,129], as reflected in the overall measure (PP5: $M = 5.68$) which fell below the average for this construct
Risk perceptions		
Safety Perceptions (SP)	- SP returned a mean score of 5.86 ($SD = 2.03$) as measured on an 11-point scale	- Safety perceptions are highly consistent across the measured items, suggesting hydrogen is viewed to be marginally safer than natural gas for heating and cooking

(*continued on next page*)

Table 1 (*continued*)

Acceptance dimension and construct(s)	Results at the construct level	Key findings and implications
	• Small difference between the five measures of SP (*SD* = 0.12)	purposes (SP1 and SP2), pipeline transportation (SP3), and underground storage (SP4)
Perceived Disruptive Impacts	• PDI returned a mean score of 2.54 (*SD* = 0.97) as measured on a 5-point scale • Small difference between the three measures of PDI (*SD* = 0.15)	• Respondents are more concerned with the prospect of being temporarily disconnected from the gas grid (PDI2; *M* = 2.64, *SD* = 0.98), whereas concerns are slightly lower regarding disruption from engineers and technicians (PDI3), and least for noise, traffic, and potential inconvenience from changes to infrastructure (PDI1)
Cost-benefit appraisal		
Perceived Socio-economic Costs (PSC)	• PSC returned a mean score of 2.87 (*SD* = 1.09) as measured on a 5-point scale • Small difference between the two measures of PSC (*SD* = 0.15)	• The perceived socio-economic costs related to fuel poverty impacts (PSC2) measured higher than energy security concerns (PSC1), however, these two items are especially interrelated and display a relatively small difference
Perceived Community Benefits	• PCB returned a mean score of 6.51 (*SD* = 2.08) as measured on an 11-point scale • Moderate difference between the five measures of PCB (*SD* = 0.44)	• Foremost, perceptions of environmental benefits (PCB3) are markedly higher than perceived economic (PCB1) and social benefits (PCB2), which explains the observed variance and suggests an underlying acknowledgement of the need for low-carbon energy technologies
Affective response		
Positive Emotions (PE)	• PE returned a mean score of 3.05 (*SD* = 0.99) as measured on a 5-point scale • Minimal difference between the four measures of PE (*SD* = 0.06)	• 'Optimism' (PE4) registered as the strongest positive emotion (*M* = 3.15, *SD* = 1.00), whereas 'satisfaction' levels (PE1) were marginally lower, followed by 'calm' (PE2) and 'confidence' (PE3) which were equivalent, suggesting that feelings of hope for a domestic hydrogen future may outweigh other positive emotions
Negative Emotions (NE)	• NE returned a mean score of 2.44 (*SD* = 1.08) as measured on a 5-point scale • Minimal difference between the four measures of NE (*SD* = 0.07)	• 'Worry' (NE2) registered as the strongest negative emotion (M = 2.55, SD = 1.06), followed by 'pessimism' (NE4), 'discontent' (NE1) and 'fear' (NE3), which had comparable mean scores, inferring that concern over hydrogen homes may outweigh other negative emotions
Social acceptance		
Domestic hydrogen acceptance (DHA)	• DHA returned a mean score of 6.39 (*SD* = 2.21) as measured on a 11-point scale • Minimal difference between the four measures of DHA (*SD* = 0.04)	• Socio-political (DHA1: *M* = 6.43); community (DHA2: *M* = 6.34); and individual acceptance (DHA3: *M* = 6.38) are comparable, indicating a relative equilibrium when accounting for the macro-, meso-, and micro-scales [33]

[a] Although this item was dropped from the Awareness (AWR) construct as reliability and validity could not be established, the data provides valuable insights.

sustained lack of public trust in financial institutions [275].

Such perspectives relay the underperformance of financial institutions in the eyes of the public, whereas renewable energy producers, and to a lesser extent GDNOs and Ofgem, are regarded as more trustworthy entities for fulfilling the net-zero mandate, although the overall prognosis remains mostly neutral. The apparent status quo resonates with findings reported by the Decarbonised Gas Alliance (DGA), wherein 36 % of survey respondents (*N* = 2000) expressed a neutral attitude regarding whether regulators such as Ofgem could be trusted to deliver a safe transition to hydrogen [116].

Thirdly, there is significant variation regarding perceptions of the respective components of the twin-track approach (see Section 3.3). A stronger preference is reported for green hydrogen (*M* = 6.86; *SD* = 0.59) compared to blue hydrogen (*M* = 6.17; *SD* = 0.85), which mirrors findings in other country contexts [119,132]. Interestingly, survey respondents expressed more support for green hydrogen in the short-term compared to the long-term (i.e. after 2030), while the reverse held true in the case of blue hydrogen. Following the logic of the twin-track approach [22], these trends are counterintuitive since blue hydrogen is anticipated to play an enabling role for facilitating the long-term move towards hydrogen production sourced from renewables [277]. Consequently, an inverse phenomenon is observed regarding public perceptions of the temporal dynamics of the twin-track approach.

Openness to blue hydrogen as a long-term production pathway (see Table 1 and Fig. A1) may reflect moderate levels of acceptance for CCS. Notably, 31 % of UK survey respondents (*N* = 4145) expressed support for CCS, while 89 % believed the technology would help combat climate change and reduce carbon emissions [274].[33] Based on available data, it can be inferred that perceptions of CCS could imply a somewhat positive outlook towards blue hydrogen, if better comprehended within the broader discussion of the hydrogen economy [129] and twin-track approach [22].

Fourthly, risk perceptions related to safety suggest that hydrogen may be viewed marginally safer than natural gas for cooking and heating applications, as well as pipeline transportation and underground storage (*M* = 5.83; *SD* = 0.12). Furthermore, the inclusion of a fifth measurement item regarding the overall safety level of hydrogen production, storage, transportation, and domestic appliances reiterates this finding (*M* = 5.68; *SD* = 1.86). By contrast, prior research has flagged sensitivities to the risks associated with hydrogen fuel in the context of transport applications [54], with moderate safety concerns expressed among German [207], South Korean [278]' and Japanese respondents [142].

Contrary to prior research [89,146], this study observes no discrepancy regarding safety perceptions for hydrogen boilers (*M* = 5.93; *SD* = 2.01) and hydrogen hobs (*M* = 5.92; *SD* = 2.04). Overall, the results align somewhat closely to studies conducted in the UK [102] and Australia [106], which suggest a mix of neutral and positive safety perceptions regarding the overall impact of blending hydrogen into the gas grid for domestic use.

Regarding perceived disruptive impacts, the results concur with findings in the literature, which cite moderate levels of preoccupation associated with the prospect of being temporarily disconnected from the gas grid [41,93]. However, impacts related to street-level disruption and visits from gas engineers appear to be more tolerable (see Fig. A2), which is also consistent with qualitative findings on this topic [41].

At the level of cost-benefit appraisal, the results align with recent data from the UK government's Public Attitudes Tracker (PAT) [100],

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[33] Additionally, 19 % of respondents were unable to give an answer (i.e. don't know), 28 % held a neutral attitude [274], and 13 % expressed strong support.

which indicates concerns over energy price hikes and fuel poverty are stronger than worries regarding reliability of energy supply. This discrepancy most likely reflects the current economic climate and ongoing energy crisis, which have exacerbated fuel poverty pressures in the UK [173]. Moreover, results from the PAT show that consumers have significantly stronger expectations for environmental benefits (see SN11), which also proved the case in this study (see Table 1 and Fig. A1).

In respect to affective response, positive emotions approximate a moderately strong response (i.e. >3), while negative emotions equate to a neutral response (i.e. ~2.5). To an extent, domestic hydrogen may induce a sense of hope and confidence among parts of the public, which outweighs alternative feelings of fear, worry, and pessimism [103]. Crucially, optimism (PE4) registered as the strongest positive emotion, while worry (NE2) proved the principal negative emotion. This result could correspond directly to a sense of optimism for a cleaner energy future, coupled to concerns over the financial costs and broader socio-economic impacts of the transition. At the same time, it may be the case that the fear factor historically associated with hydrogen [279,280] is diminishing over time [145].

Additionally, the descriptive results for the endogenous construct, Domestic Hydrogen Acceptance (DHA), suggest strong convergence when considering consumer perceptions across macro-, meso-, and micro-levels [33], as demonstrated in Fig. A1. However, it is anticipated that these dimensions may fluctuate by different magnitudes and possibly in alternative directions following the development of local hydrogen activities. Ruptures in public opinion and diverging consumer attitudes have already been witnessed in a short timeframe vis-à-vis the emergence of social resistance [281], which culminated in cancellation of the Whitby village trial (Ellesmere Port) in July 2023 [282] and has cast doubt over the viability of future trials [283].

6.2. Measurement model assessment

This study operationalises ten exogenous constructs and one endogenous construct, which are measured reflectively. Whereas a formative construct is caused by its indicators – with arrows pointing towards the construct – in a reflective model the latent construct exists (in an absolute sense) independent of its indicators [284]. Thus, variation in the construct causes variation in the measurement items, but the items do not cause variation in the construct [284,285]. Therefore, in a reflective model, arrows point from the construct to the indicators, since items are highly correlated and interchangeable [286], as is the case in this study.

For example, indicators such as economic, social, and environmental benefits are assumed to be influenced by an underlying latent construct [287,288], namely, perceived community benefits. More technically, the set of indicators represents a "measurement error-prone manifestation" of the underlying latent construct [[248]:3]. When measuring reflective constructs, four criteria should be met: item reliability, internal consistency reliability, convergent validity, and discriminant validity [288]. Critically, an instrument cannot be considered valid unless reliability is first established [290].

6.2.1. Item reliability and internal consistency reliability

Item reliability is concerned with whether a measurement instrument performs consistently (i.e. scale reliability), which can be assessed using Cronbach's Alpha (CA).[34] Reliability is best supported when an indicator loading measures above 0.708 [291], which implies that the construct accounts for >50 % of the indicator's variance [48]. Two indicators fell marginally below the preferred threshold value, namely, ST1 (0.698) and DI1 (0.687), which is unproblematic for exploratory social science research involving new measurement items [286,292]. Although PP1 (0.550) had a relatively low CA, this indicator also warranted retention since related reliability and validity requirements were fulfilled [286,292].[35]

Table 2
Assessment of reliability, convergent validity, and multicollinearity.

Construct	CA	CR (ρ_A)	CR (ρ_C)	AVE	VIF
Awareness	0.797	0.836	0.906	0.829[a]	1.346
Public trust	0.864	0.890	0.900	0.644	1.504
Production Perceptions	0.816	0.845	0.870	0.578	1.599
Safety Perceptions	0.918	0.920	0.939	0.754	1.575
Perceived Disruptive Impacts	0.758	0.813	0.859	0.673	1.259
Perceived Socio-economic Costs	0.730	0.736	0.881	0.787[a]	1.427
Perceived Community Benefits	0.808	0.813	0.886	0.721	2.066
Positive Emotions	0.881	0.885	0.918	0.737	1.468
Negative Emotions	0.869	0.900	0.909	0.715	1.409
Domestic Hydrogen Acceptance	0.922	0.922	0.951	0.865	n/a

[a] Since Awareness (AWR) and Perceived Socio-economic Costs (PSC) have two indicators, the AVE is by default larger than 0.50. The result is reported for consistency.

Composite Reliability (CR) provides a better measure of internal consistency than CA, since items are weighted according to the individual indictor loadings per construct [48].[36] Homogeneity is supported when CR values exceed 0.70 [286], while ≥0.60 is acceptable for exploratory research [293] such as this study. As reported in Table 2 (see SN8), both measures of CR exceeded 0.70 [48,294] (i.e. Dillon-Goldstein rho_c (ρ_C) and Henseler and Dijkstra rho_a (ρ_A)).

6.2.2. Convergent validity and discriminant validity

Convergent validity is concerned with whether each construct converges to explain the variance of its indicators [48], which was met since the average variance extracted (AVE) exceeded 0.5 for all constructs [286,293], as reported in Table 2. Relatedly, discriminant validity assesses whether a construct can be considered empirically distinct within the model [48]. Thresholds for establishing discriminant validity were met, as reported in Table 3 and described in Appendix C (see Table A2 and SN8). Finally, no instances of multicollinearity were observed, variance inflation factor (VIF) scores were below the more stringent threshold of 3.0 in all cases [291].

6.3. Structural model assessment

The bootstrap method with 5000 sub-samples was applied to test the direction, strength, and significance of proposed hypotheses [269], as reported in Table 4. Firstly, cognitive processes – awareness (AWR) and knowledge (KNW) – had a non-significant effect on social acceptance, although awareness exerted a stronger influence between the two constructs. This result suggests a consistent dynamic between awareness and knowledge, whereby these interrelated constructs mirror one another as poor predictors of domestic hydrogen acceptance at this stage of the transition.

Public trust (PT) had a positive and significant influence on domestic hydrogen acceptance, implying that the transition will be influenced by public perceptions related to the capabilities and credibility of different actors and stakeholders. Regarding the environmental dimension linked specifically to production perceptions (PP), a significant positive effect is observed, which can be traced foremost to consumer preferences for a green hydrogen pathway, as described in Section 3.3.

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[34] Calculated according to the average covariance divided by the average total variance (i.e. the average correlation shared between indicators and a given latent construct [294]).

[35] Importantly, it is more conceptually sound to retain an indicator for content validity than to remove it purely on grounds of a low CA value [292].

[36] Since items are unweighted, CA tends to underestimate internal consistency reliability [49].

Table 3
Heterotrait-monotrait results for assessment of discriminant validity.

	AWR	PCB	PDI	KNW	NE	PSC	PE	PP	SP	DHA	ST
AWR											
PCB	0.111										
PDI	0.064	0.197									
KNW	0.537	0.086	0.094								
NE	0.080	0.256	0.511	0.113							
PSC	0.073	0.437	0.392	0.161	0.530						
PE	0.294	0.527	0.153	0.297	0.115	0.249					
PP	0.247	0.638	0.193	0.244	0.237	0.329	0.404				
SP	0.088	0.640	0.036	0.135	0.125	0.159	0.403	0.413			
DHA	0.190	0.779	0.346	0.159	0.376	0.438	0.610	0.673	0.518		
ST	0.235	0.520	0.144	0.250	0.118	0.122	0.428	0.473	0.488	0.588	

Table 4
Results of path analysis and hypothesis testing.

Hypothesis	β coefficient (*SD*)	*t*-statistic	ρ-value	f^2	Result
H1: AWR ➔ (+) DHA	0.019 (0.015)	1.236	0.217	0.001	Rejected
H2: KNW ➔ (+) DHA	−0.008 (0.016)	0.513	0.608	0.000	Rejected
H3: PT ➔ (+) DHA	0.198 (0.02)	10.207	<0.001	0.079*	Accepted
H4: PP ➔ (+/−) DHA	0.214 (0.02)	10.897	<0.001	0.086*	Accepted
H5: SP ➔ (+/−) DHA	0.058 (0.02)	2.883	0.004	0.006	Accepted
H6: PDI ➔ (−) DHA	−0.092 (0.017)	5.450	<0.001	0.020	Accepted
H7: PSC ➔ (−) DHA	−0.058 (0.017)	3.432	0.001	0.007	Accepted
H8: PCB ➔ (+) DHA	0.276 (0.023)	12.118	<0.001	0.111*	Accepted
H9: PE ➔ (+) DHA	0.217 (0.017)	12.599	<0.001	0.097*	Accepted
H10: NE ➔ (−) DHA	−0.138 (0.017)	8.325	<0.001	0.041*	Accepted

[*] Small effect (i.e. >0.02).

In terms of perceived risks, safety perceptions (SP) of hydrogen and the perceived disruptive impacts (PDI) of the switchover process are seen to largely neutralise one another. Nevertheless, the negative effect stemming from perceived disruptive impacts ($\beta = -0.092$, $t = 5.450$, $\rho \leq 0.001$) exceeds the positive association between safety perceptions and social acceptance ($\beta = 0.058$, $t = 2.883$, $\rho = 0.004$), which suggests risk perceptions are somewhat prominent.

At the level of cost-benefit appraisal, perceived community benefits is the strongest predictor of domestic hydrogen acceptance ($\beta = 0.276$, $t = 12.118$, $\rho \leq 0.001$), whereas perceived socio-economic costs is a comparatively weak predictor ($\beta = 0.058$, $t = 3.432$, $\rho = 0.001$) but still significant as the 1 % level. While consumers anticipate socio-economic advantages through the acquisition of domestic hydrogen, there is stronger expectancy for environmental benefits. Lastly, both affective constructs (PE and NE) shape consumer attitudes towards hydrogen, with positive emotions exerting more influence than its negative counterpart.

Among the ten exogenous constructs incorporated in this study, eight proved significant predictors of domestic hydrogen acceptance at the 1 % level ($\rho < 0.01$), with awareness and knowledge proving non-significant at this early stage of the technology life cycle (see Fig. 2 and SN9) [295]. Accordingly, constructs belonging to the cognitive dimension returned insignificant effects, whereas other dimensions proved significant at the 1 % level.

In summary, the following constructs have a small effect on social acceptance (i.e. $f^2 \geq 0.02$): public trust; production preferences; perceived community benefits; positive emotions; and negative emotions. However, safety perceptions, perceived disruptive impacts, and perceived socio-economic costs fall below the cut-off value suggested by Cohen [296]. Foremost, the dimensions of environmental attitude (i.e. production perceptions), affective response (i.e. positive and negative emotions), and social capital (i.e. public trust) predict social acceptance to a similar extent, followed by cost-benefit appraisal (i.e. perceived socio-economic costs and perceived community benefits), and risk perceptions (i.e. safety perceptions and perceived disruptive impacts), as reported in Table A3.

6.4. Importance-performance map analysis

As a decision-making tool [297,298], importance-performance map analysis (IMPA) [299] provides a means for deriving additional insights at both the construct and indicator level, thereby enabling triangulation with descriptive findings (see Section 6.1) and PLS-SEM results (see Section 6.3). The IMPA plots unstandardised total effects (i.e. importance on the x–axis) against the average value of latent variable and their indicators on a scale of 0–100 (i.e. performance on the y–axis) to identify areas of strategic relevance [258]. Foremost, constructs located at the bottom far quadrant of the IMPA – corresponding to high importance but low performance for domestic hydrogen acceptance – signify opportunities for leveraging interventions [258]. Thus, IMPA aids in identifying constructs of strategic value [299–301], which may be targeted through subsequent policy making efforts, communication campaigns, and managerial action [302,303].

Increasingly, sustainability scholars have adopted IMPA [304], as a tool to support optimal resource allocation strategy [303] and strategic decision-making in a range of contexts (see SN10). Moreover, internalising results from an IMPA is especially critical during times of economic instability [305] such as the current energy crisis [173,306]. To carry out an IMPA, the guidelines provided by Ringle and Sarstedt [299] are applied to better understand the influence of endogenous constructs (see Section 6.4.1) and specific indicators (see Section 6.4.2).

6.4.1. IMPA for endogenous constructs

Firstly, an IMPA is carried out for the direct predecessors of domestic hydrogen acceptance, as visualised in Fig. 3 (see SN10). Among the ten exogenous constructs analysed, negative emotions and perceived disruptive impacts rank in the middle in terms of importance: PCB, PE, PP, ST, **NE**, **PDI**, SP/PSC, AWR, KNW. There is clear overlap and interacting effects between the positive side of the hydrogen acceptance matrix [103] focused on perceived community benefits, production preferences, and public trust. These areas transmit to higher levels of optimism, confidence, and satisfaction with the promise of socio-economic and environmental benefits through the deployment of

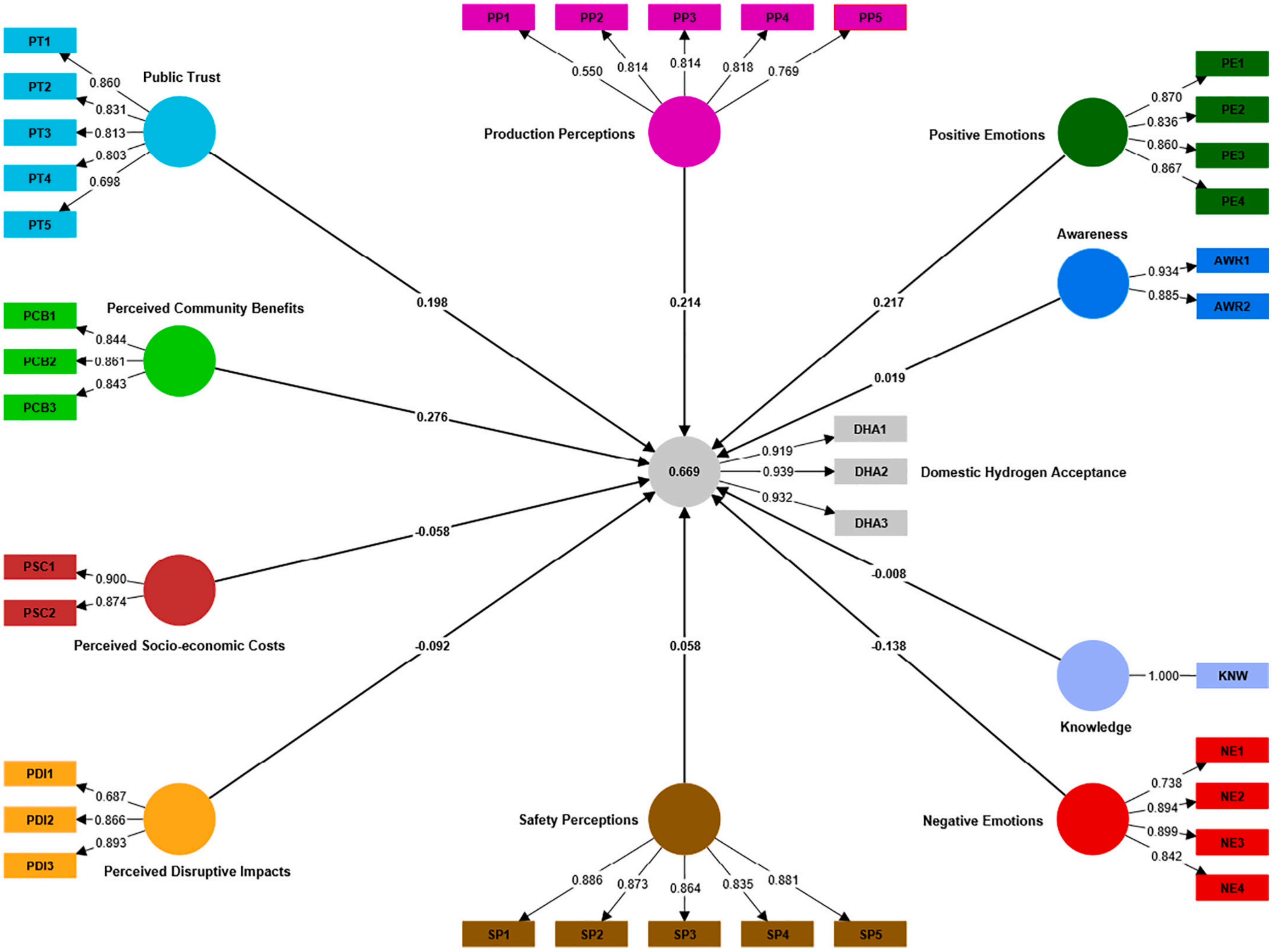

Fig. 2. Structural model path coefficients.

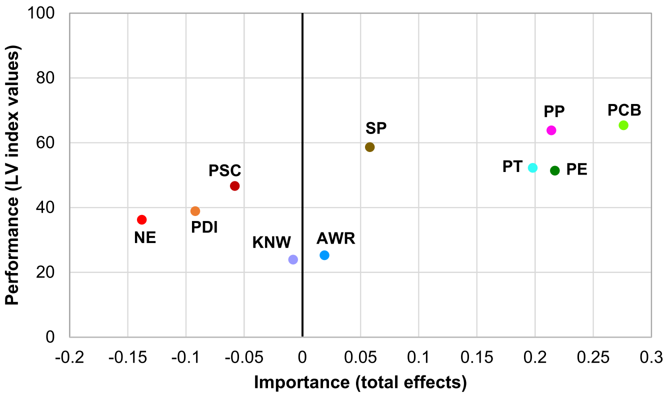

Fig. 3. Importance-performance map analysis for endogenous constructs. Blue = Awareness (AWR); Lilac = Knowledge (KNW); Turquoise = Public Trust (PT); Lavender = Production Preferences (PP); Brown = Safety Perceptions (SP); Orange = Perceived Disruptive Impacts (PDI); Dark red = Perceived Socio-economic Costs (PSC); Bright green = Perceived Community Benefits (PCB); Dark green = Positive Emotions (PE); Red = Negative Emotions (NE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hydrogen homes.

Interestingly, safety perceptions and perceived socio-economic costs have equal total effects, but are separated on the IMPA due to their respective positive and negative influence on social acceptance. The two constructs are further distinguished in terms of their performance metrics, with safety perceptions outperforming perceived socio-economic costs by 12 units. As a result, there is more strategic value in targeting improvements in perceived socio-economic costs when choosing between these two constructs in isolation (see SN10). However, as illustrated by the rank order, neither construct falls within the priority cluster for bolstering social acceptance more directly. The IMPA further corroborates the weak impact of awareness and knowledge at this stage of the transition, while underscoring the importance of perceived community benefits.

6.4.2. *IMPA for construct indicators*

To complete the assessment, the analysis is extended to the indicator level (see SN10). Fig. 4 displays indicators with an effect size of 0.05 and higher,[37] which account for the following constructs: perceived community benefits (all indicators); positive emotions (all indicators); production perceptions (excluding PP1); and public trust (excluding PT3

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[37] The x-axis is reduced to 0.04 to account for this cut-off value and increase readability.

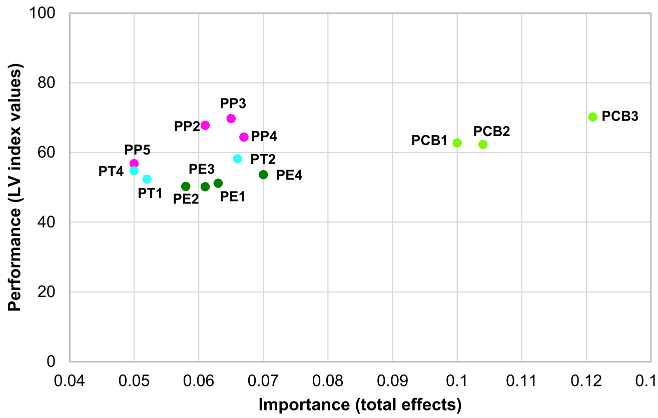

Fig. 4. Importance performance map analysis for top 14 indicators. Turquoise = Public trust (PT); Lavender = Production Preferences (PP); Bright green = Perceived Community Benefits (PCB); Dark green = Positive Emotions (PE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and PT5).

The following conclusions can be drawn which support observations from the descriptive statistics reported in Section 6.1. Firstly, indicators related to perceived community benefits represent the foremost target area for elevating social acceptance, with environmental benefits (PCB3) carrying the most potential impact and outperforming economic (PCB1) and social benefits (PCB2), as well as all other indicators.

Interestingly, this result contradicts one study conducted in the North of England ($N = 578$), wherein survey respondents perceived significantly higher socio-economic benefits from hydrogen, as opposed to environmental benefits [117]. However, the study in question [117] had an inherently industrial and place-specific framing around efforts to establish a ‘UK hydrogen corridor’ between Leeds and Teesside, which likely explains why respondents envisioned substantial socio-economic benefits around job creation and industrial reinvigoration.

Overall, the IMPA aligns to results from the PAT [100], which showed that self-rated happiness (i.e. consumer acceptance) in relation to local energy infrastructure (i.e. onshore wind farms and solar panel farms) stems primarily from the perception of environmental benefits, whereas socio-economic benefits are of secondary importance [100] (see SN10). Furthermore, support for more traditional renewables such as onshore wind and solar farms is strongly linked to perceptions regarding emissions reduction [274], underlining the importance of perceived environmental impacts.

Secondly, there is little to distinguish between the four positive emotions measured in this survey, although optimism presents additional importance for garnering social acceptance. Notably, positive emotions stem from reactions towards other factors such as costs, benefits, and risks, which may explain why this construct has a mid-level performance. Accordingly, the IMPA suggests more resources should be allocated towards promoting a green hydrogen production pathway (PP3 and PP4) in line with the promise of environmental benefits, which may reinforce positive perceptions and emotions. To this end, evidence suggests that renewable energy producers (PT2) are the most trusted entity for supporting the hydrogen transition.

It follows that renewable energy producers have a primary role in supporting the social acceptability of the hydrogen homes, while GDNOs (PT1) and Ofgem (PT4) have a complementary responsibility, which is somewhat more secondary in the eyes of the public at the present time. However, it should be stressed that the collapse of the Whitby village trial may have cast significant public doubt over the capabilities and intentions of GDNOs [307,308], which would need to be rapidly reversed if domestic hydrogen is to be given a green light by the government after 2026 [22].

6.5. *Assessment of predictive power*

Traditionally, PLS-SEM practitioners have relied on assessing the path model’s in-sample explanatory power [250,309], which is typically assessed using the coefficient of determination (R^2) [79]. R^2 reports the proportion of variance in the endogenous construct (i.e. domestic hydrogen acceptance) that can be explained by other constructs in the model. However, R^2 offers no specific guidance as to the out-of-sample predictive power of the model, which requires “estimating the model on a training (analysis) sample and evaluating its predictive performance on data other than the training sample” [[270]:2324].

Thus, as a causal-predictive modelling approach [310], it is important to evaluate results from PLS-SEM in terms of both explanatory and predictive power [251,309,311]. Foremost, adherence to assessing out-of-sample predictive power is critical for theory development and validation, in addition to determining whether the modelling results can reliably inform policy making and strategic planning for a prospective transition to hydrogen homes.

6.5.1. *In-sample predictive power*

As a rule of thumb, Henseler et al. [238] suggest that R^2 values of 0.25, 050, and 0.75 correspond to weak, moderate, and strong effect sizes. However, lower R^2 values are anticipated and acceptable when examining emerging phenomena, such as low-carbon energy acceptance [261] or social media-related behaviour [289]. Therefore, R^2 should be considered as relative measure, whereby lower values typically reflect the exploratory nature of emerging social science research [312]. In this study, R^2 measured 0.669, suggesting a moderate to strong level of in-sample predictive accuracy, reflecting the model’s explanatory power.

6.5.2. *Out-of-sample predictive power*

Predictive benchmarking provides researchers with insights as to whether the proposed model outperforms a naïve baseline [242,313]. The quality of the structural model and its predictive relevance can be assessed through the blindfolding procedure [260], which returns the Stone-Geisser’s Q^2 value [314,315].[38] To better examine a model’s out-of-sample predictive power [316], Shmueli et al. [[270]:2322] developed the PLSpredict tool: “a holdout-sample-based procedure that generates case-level predictions on an item or a construct level to reap the benefits of predictive model assessment in PLS-SEM.”

More recently, Liengaard et al. [79] introduced the cross-validated predictive ability test (CVPAT) to further compare the predictive capabilities of different models. The CVPAT functions by performing “a pairwise comparison between theoretically derived competing models,” and then “selecting the model with the highest predictive power based on a prespecified statistical significance level” [79].

According to the PLSpredict results, only one indicator (DHA2) outperformed the naïve linear model (LM), which suggests low out-of-sample predictive power for the model. However, based on results from the CVPAT, the proposed model demonstrated high predictive power, since the average loss difference between the PLS-SEM model and the indicator average (IA) was negative (−2.795) [79]. Consequently, the PLS-SEM model outperformed the LM benchmark in relation to the endogenous construct, social acceptance, as reflected by a statistically significant result ($t = 20.971$, $\rho \leq 0.001$). In view of both assessments, it may be concluded that the proposed model demonstrates a moderate level of out-of-sample predictive power (see Table 5), which is supported by Q^2 values >0.50.

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[38] Shmueli et al. [251] further explain that since the Q^2 draws on single omitted and imputed data points, as opposed to holdout samples, the metric is essentially “a combination of in-sample and out-of-sample prediction,” but doesn’t explicit indicate the level of explanatory power (i.e. R^2 value) or predictive power of the model.

Table 5
Results of predictive power using PLSpredict.

Items	Q^{2}predict	Root mean square error (RMSE)[a]	Mean absolute error (MAE)[b]		
		PLS-SEM	Linear model	PL-SEM	Linear model
DHA1	0.583	1.359	1.342	1.047	1.021
DHA2	0.583	1.442	1.448	1.112	1.114
DHA3	0.556	1.520	1.514	1.167	1.163

[a] The square root of the average of the squared differences between the predictions and the actual observations [236,317].

[b] The square root of the average of the squared differences between the predictions and the actual observations [317].

6.6. *Links between acceptance dimensions and constructs*

6.6.1. *Cognitive processes*

Supporting findings in the literature [129,318], this study suggests cognitive processes linked to awareness and knowledge of hydrogen are currently non-significant factors of domestic hydrogen acceptance. It follows that subjective knowledge may prove a less influential acceptance factor during the early stage of technology transitions when information is somewhat scarce, and plans remain more dynamic or tentative [22,23].

When confronted with a knowledge deficit or faced with highly complex or technical information, consumers may bypass deep cognitive evaluations in favour of emotional responses which can act as decision-making heuristic [319]. In accordance with findings in the literature [32,39], it follows that domestic hydrogen remains at the periphery of public thinking [101,102], which may constrain the influence of awareness and knowledge on social acceptance during the formative phase of the transition.

6.6.2. *Social capital*

The results suggest public trust is a positive and significant predictor of domestic hydrogen acceptance, thereby establishing the importance of social and cognitive processes, whereas cognitive aspects in isolation are less impactful. This finding supports a rich literature documenting the role of public trust in shaping the acceptance of emerging energy technologies [38,74,320]. It is apparent that developing public trust in hydrogen production pathways, energy markets, and management of pipeline infrastructure is critical to the transition. By the same token, trust dynamics concerning the investment landscape and publicising of domestic hydrogen will shape prospects for the transition. Foremost, public trust may prove a prerequisite to enabling consumer confidence in the environmental, economic, and social benefits of hydrogen homes [117,321]. Public trust in the domestic hydrogen transition will be strengthened if stakeholders enshrine maximum commitments towards ensuring environmental health and human safety.

6.6.3. *Environmental attitude*

This study explored perceptions of hydrogen production pathways vis-à-vis the government's twin track approach, thereby gauging potential (environmental) preferences for blue and green hydrogen production [129]. At one level, Table 1 and Fig. A1 support qualitative results highlighting an implicit misunderstanding about the rationale of the twin-track approach [129]. Nevertheless, the prognosis for social acceptance appears to lie with scaling up green hydrogen production, which aligns to most international findings [69,119,322]. Addressing misconceptions in the public sphere, which entails an important role for energy representatives, politicians, and media outlets, is crucial to legitimising the UK Hydrogen Strategy [22].

At present, evidence suggests the inferred equivalence or balancing of the twin-track approach is unrecognised by the public, which obscures the apparent commitment towards ensuring complementarity over competition in realising the hydrogen economy [31]. While blue hydrogen is likely a necessity for achieving industrial decarbonisation [7], and may underpin the foundations of developing a national hydrogen economy in the UK [22],[39] a clear and direct public communication campaign on hydrogen production pathways is yet to be invested in.

6.6.4. *Risk perceptions*

As reported via descriptive analysis, both safety and disruptive impacts are perceived to be somewhat moderate. The former construct (SP) has a positive influence on social acceptance, owing to a general perception that hydrogen may be slightly safer than natural gas, whereas the latter (PDI) exhibits a negative association. Given the reported awareness and knowledge deficit, it is conceivable that the risk characteristics of hydrogen remain poorly understood by most consumers.

The results suggest consumers consider hydrogen fuel to incur similar risks to natural gas [323,324], which is partially consistent with findings in the literature [93,102,106]. At the same time, it is apparent that safety perceptions may vary according to different HETs, while cross-cultural differences could explain discrepancies in the recent literature. Additionally, it has been shown that support for HETs is positively associated to public trust in the provision of adequate safety precautions [69,93], which may be the presumption among respondents in this survey.

On the softer side of hydrogen-related risks, it is logical that consumers would wish to minimise the extent of disruptive impacts during the switchover process. However, whereas a recent literature review suggested the disruptive impacts of the switchover may rank as a 'major' barrier to domestic hydrogen acceptance [32], this study identifies this construct to be a somewhat less critical barrier.

Overall, it can be asserted that taken together, safety perceptions and perceived disruptive impacts have a largely neutralising effect on risk perceptions. Nevertheless, the perceived risks of hydrogen may be prone to sudden changes when activities are taken from the hypothetical to the real [325–327] and moreover, in the event of inevitable safety incidents [328,329].

6.6.5. *Cost-benefit appraisal*

The wider energy acceptance and emerging hydrogen acceptance literatures suggest perceived benefits may be the foremost predictor of social acceptance and technology adoption [39,178,187], which was corroborated in this study. Beyond the UK context (see Section 3.3), the modelling results echo findings from Norway, wherein perceived environmental benefits proved an important predictor of hydrogen acceptance [119]. Notably, the Norwegian study flagged the need to consider other acceptance factors such as "perceived cost, safety and economic benefits" [[106]:10], which has been addressed in this study but likewise requires further comparative assessment.

Perceptions of socio-economic costs are set to fluctuate according to the macro-economic environment, which currently dictates greater levels of concern over fuel stress implications than national energy security issues (see Table 1, Fig. A2). However, these two areas are highly intertwined, with the former capturing the more personal dimension against the socio-political dimension of the energy crisis. Given the premise that industrial reinvigoration and levelling up [41,330] should be embedded into the hydrogen transition [22], failure to create an acceptable safety net for households in fuel poverty and socio-economically deprived regions could lead to widespread social resistance.

6.6.6. *Affective response*

In addition to perceived benefits, emotional responses may be among

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[39] Alongside other countries such as Germany [277], Australia [401], and Japan [72].

the most critical predictors of HET acceptance [39], which proved the case in this study. Emotional responses may exhibit a comparatively stronger influence in the domestic energy context [192,331], wherein the lived experience of heating and cooking impacts consumer expectations and preferences [89,102]. Foremost, this study finds that positive emotions have a stronger influence on social acceptance than negative emotions, although the latter construct is also significant at the 1 % level.

Ambitions for accelerating industrial decarbonisation are a driver of large-scale (hydrogen) production [7], which strongly underlies the techno-economic feasibility of hydrogen homes [31]. In parallel, policy and market decisions around the role of heat pumps [332,333], smart hybrid heat pumps [334], and other low-carbon technologies such as district heat networks [335] will shape emotional responses to hydrogen home appliances.

Given the interdependencies between energy resources and different hydrogen production pathways [336,337], 'perception spillover' effects may influence the acceptance dynamics of the broader hydrogen economy [338]. Notably, Westlake et al. [338] highlight the extent to which perception spillover from one energy technology such as fracking may influence public attitudes towards emerging low-carbon solutions. Specifically, the moratorium on fracking appears to have undermined the social acceptance of deep 'enhanced' geothermal systems compared to green hydrogen [338], which could present a cautionary tale for CCS and blue hydrogen [339].

7. Conclusions

As remarked by Parkison et al. [128], highly technical data on costs and emissions is often leveraged and misrepresented by groups with vested interests to sway policy makers and influence public opinion, especially in respect to the polarising debate around fossil-based and renewable-based hydrogen production technologies. Accounting for these dynamics, this study presents key findings on domestic hydrogen acceptance, as transmitted by the public and made accessible to a wide range of stakeholders through data visualisation techniques.

This research bridges a critical knowledge gap in the energy acceptance literature by comprehensively examining public perceptions of domestic hydrogen. In parallel, this study motivates the wider dissemination of PLS-SEM in energy acceptance research to support a deeper understanding of the conditions for accelerating low-carbon energy adoption. The following sub-sections complete the analysis by outlining key theoretical and empirical contributions, future research avenues, and practical implications which can be leveraged by policy makers and key stakeholders to support a 'hot transformation' for the residential sector [340].

7.1. Theoretical and empirical contributions

This research contributes to theory by developing and empirically validating a novel model of domestic hydrogen acceptance, which is conceptualised in Fig. 1. While prior work has explored the foundations for conceptualising a definitive framework [33,39,69], this study is the first to formalise a multi-dimensional model, while validating its explanatory and predictive capabilities using PLS-SEM. The DHAM is composed of ten exogenous constructs which underpin six socio-psychological dimensions, wherein five proved significant at the 1 % level (Table A3).

It can be concluded that these dimensions and their corresponding constructs are significant predictors, together explaining nearly 67 % of domestic hydrogen acceptance. Consequently, the model validates the efficacy of eight constructs (PT, PP, SP, PDI, PC, PCB, PE, and NE), although two constructs at the cognitive dimension (AWR and KNW) proved insignificant. Accordingly, this study makes an important empirical contribution, which may stimulate subsequent engagement with PLS-SEM by hydrogen acceptance scholars. Notably, the need for this trajectory has been recognised by Harichandan and colleagues [261,262,341] when validating hypotheses in the context of HFCV adoption in India.

The DHAM provides the research community with a baseline model for examining consumer attitudes towards hydrogen homes. Findings from this research can be benchmarked against statistical results from other country contexts such as Australia [69] to help bridge conceptual and empirical understanding on hydrogen acceptance. Critically, this analysis reinforces the call for more robust quantitative assessments [39] to advance understanding on developing national hydrogen economies. Developing models with stronger explanatory and predictive power is a critical mechanism for embedding societal factors in the technological pursuit of large-scale, sustainable energy solutions, which may include establishing a global hydrogen economy.

7.2. Scope for developing the DHAM and future research agenda

This study focused exclusively on modelling direct relationships between latent constructs. However, prior research highlights the value of considering the mediating role of constructs such as public trust [320], and perceived risks, costs, and benefits [74,261,342]. For example, Montjin-Dorgelo [206] modelled trust and emotions as mediators when examining acceptance for hydrogen buses in the Netherlands, while Yang et al. [206,320] proposed a mediating role for public trust in the context of CCS technologies in China.

In addition to testing for mediation and moderation effects, further conclusions can be drawn by expanding the multi-dimensionality of certain constructs through new measurement items. For example, survey items corresponding specifically to perceived economic, social, and environmental benefits would facilitate opportunities for developing a reflective-formative construct to increase theoretical parsimony and reduce model complexity [343], as illustrated in Supplementary Note 12 (SN12).

Researchers may also adapt and extend the DHAM by developing a higher-order construct for public trust. Given the importance of public trust to facilitating energy acceptance and technology adoption, further modelling work is needed to evaluate consumer perspectives towards the government, energy industry, and other key stakeholders, as potential enablers of a socially acceptable transition to hydrogen homes. To this end, researchers can leverage opportunities to integrate additional constructs into the DHAM to unpack the trust dynamics of the domestic hydrogen transition.

Higher-order constructs could also be a viable technique for modelling production perceptions (i.e. operationalising blue and green hydrogen as lower-order constructs). Notably, a recent UK study asked respondents about their level of agreement regarding government investment in hydrogen production funded by a levy on people's energy bills [344], which could be used as a construct indicator in future studies. It follows that distilling socio-economic and environmental perceptions of hydrogen production pathways presents a fruitful area for further research. In sum, the baseline version of the DHAM can motivate more nuanced studies which employ techniques such as mediation and moderation analysis to model hydrogen acceptance [345,346].

At the construct level, follow-up studies should further evaluate the cognitive dimension and explore additional measurement items to validate and extend findings from this case study. A recommended approach is to examine potential differences between consumer segments via a multigroup analysis (MGA) [82,347]. The efficacy of MGA has been demonstrated across a range of technology acceptance studies [348–350], leading to recent uptake among energy scholars [318,351]. MGA can help expand the evidence base, while supporting longitudinal, cross-cultural hydrogen acceptance studies. Future studies can also crystallise insights on perceived disruptive impacts by validating whether current assessments suggesting a tolerance period of around three days are accurate [41], while further clarifying the scope of expectations among different consumer segments [146,222].

Although the critical findings on cost-benefit appraisal are strongly supported by government data (see SN11), cross-comparative analysis of large datasets should be carried out to further validate the findings. Importantly, the selected survey instruments encountered a notable constraint for achieving a more robust comparison between perceived costs and benefits. Specifically, an intended third measure (i.e. negative environmental impacts) of the original construct, *perceived costs*, could not be validated. This discrepancy may partially explain why the cost-benefit appraisal dimension is somewhat less significant than other dimensions (i.e. social trust, cognitive processes, environmental attitude, and affective response), as reported in Table A3.

In follow-up research, the selected statement, "Switching from natural gas to hydrogen will have an insignificant impact towards reaching 'net-zero' (i.e. a reduction of the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050)," can be simplified to "*Switching from natural gas to hydrogen will have negative environmental impacts*" to establish construct validity. Despite this limitation, the modelling results provide critical insights regarding the pivotal dimension of cost-benefit evaluations, as highlighted in Section 6.6.6.

There is also scope for better capturing the affective dimension through a wider range of emotional responses. Notably, the seminal study of Beaudry et al. [352] provides a robust framework for evaluating affective appraisals in relation to emotions concerning achievement (e.g. satisfaction), challenge (e.g. hope), loss (e.g. anger), and deterrence (e.g. fear). If follows that additional survey instruments are required to better account for the wide spectrum of emotional responses to domestic hydrogen [103].

Furthermore, multiple evidence streams are needed to ascertain whether positive emotions towards domestic hydrogen prevail, and moreover, how the dynamics of emotional response may change over time in accordance with different policy prescriptions [353], party preferences [354], and media representations [355,356]. Additionally, important insights could be extracted by comparing social acceptance across different measures in relation to hydrogen, CCS, nuclear and wind energy (onshore and offshore), thereby elucidating statistical relationships between these interrelated technologies, which would advance the contribution of Roddis et al. [357].

7.3. Practical contributions and policy implications

Beyond the theoretical dimension, there are several practical implications of this research. The study provides policy makers and key stakeholders such as GDNOs and boiler manufacturers with strategic insights for improving consumer engagement, information campaigns, and management decisions. Fig. 4 clearly translates the implications of the model, communicating the underlying need to couple green hydrogen production to community benefits, as a mechanism for increasing optimism and confidence in hydrogen homes.

At the same time, stakeholders should not overlook the importance of managing the disruptive impacts of the transition ahead of time, while pre-empting the risks of negative socio-economic effects. Such measures would help simmer negative emotions towards hydrogen at a time when energy vulnerabilities are high [173,358], as geopolitical stakes continue to increase around resources [169,170,359] and ideologies [166,360].

As the stakes for deploying low-carbon technologies continue to rise, this analysis can help steer critical discussion around potential synergies between hydrogen production pathways and community benefits to support a socially acceptable energy transition. In response, UK policy makers and key stakeholders should seek to leverage prospects for better packaging the synergistic effects of scaling up different hydrogen production methods.

This measure could help support a more positive environmental attitude towards hydrogen across society, which may involve reconsidering the 'twin-track' framing, in view of its propensity for raising confusion, doubts, and scepticism among the public. Recasting the twin track production approach and justifying the role of blue hydrogen to the public are important starting points for facilitating social acceptance. In doing so, the government can take strides towards building knowledge and awareness of hydrogen across society and supporting public trust in the hydrogen economy.

Government policies should aim to ensure 'price promises' [361] on hydrogen boilers are delivered by manufacturers to counteract perceived socio-economic risks. Furthermore, the government should dedicate adequate resources towards alleviating fuel poverty pressures, as part of its residential decarbonisation strategy and wider net-zero agenda [41,173]. Such measures would help improve public expectations for economic and social benefits trickling down to the community level [117].

Emotional responses to hydrogen may underlie social acceptance, especially at the individual and community level [39], with implications for attitudes towards safety, production, risks, costs, and benefits [44,191]. Strengthening positive emotions will weaken the impact of potential negative feelings towards hydrogen, which can be addressed more directly by minimising concerns over perceived socio-economic costs and disruptive impacts, while ensuring safety perceptions are decoupled from fears and negative imagery.

7.4. Supporting a hot transformation via hydrogen homes?

History has shown that a large-scale conversion to a new gas supply is plausible, both in the UK [159] and internationally [362,363], however, this era calls for a 'hot transformation' [340] which is clean, equitable, and timely. Agents of the energy transition including policy makers, GDNOs, and boiler manufacturers may leverage insights from this study to devise more holistic and reflexive solutions to instilling social acceptance into the fabric of the hydrogen transition. As noted by Papachristos [[364]:57] governance approaches for mitigating climate change call for "an iterative process of problem definition, intervention and response" to bridge the gap between different actor groups in pursuit of productive dialogues and constructive actions [365].

A hybrid, collaborative approach is needed to realise the potential economic, social, and environmental benefits of the hydrogen economy [16,366]; bearing in mind that the techno-economic feasibility of hydrogen homes and other HETs [31] must be established to facilitate social acceptance. Foremost, the implementation of HETs will be driven by cost factors and scalability [19,128], wherein techno-economic constraints must be tackled to support national hydrogen economies [19]. This calls for a whole-systems approach geared towards leveraging the synergistic benefits of hydrogen production pathways, thereby advocating for complementarity over competition in delivering the twin-track approach [31].

A more unified vision between stakeholders supporting respective green gas [367–369] and electrification pathways [370,371] is desirable. Ideally, rifts between incumbents and new entrants should be narrowed by the vision (or re-envisioning) of the twin-track approach, and moreover, the pressing need to accelerate 'deep' decarbonisation [372]. Stronger levels of collaboration and unity could bolster public trust in the transition, while promoting the underlying tenets of the twin-track approach, which is needed to consolidate community and socio-political acceptance.

Ahead of a critical decision on the future of residential decarbonisation in the UK towards the mid-2020s [22,335], energy scholars should respond in kind by accelerating the adoption of state-of-the-art predictive modelling approaches. In conjunction with PLS-SEM, emerging methods such as machine learning [373,374] and artificial neural networking [375,376] should be harnessed as complementary techniques to enhance critical insights on domestic hydrogen acceptance.

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, Methodology, Project administration, Supervision.

Anwar Haq: Conceptualization, Methodology, Writing – original draft. **Seyed Ali Nabavi:** Conceptualization, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

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

Data availability

Data will be accessible publicly on our institutional data repository https://doi.org/10.17862/cranfield.rd.24517966.v1.

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Appendix A. Sample characteristics

Table A1
Sample characteristics and comparison to UK population.

Socio-demographic variable	Sample (%)	UK population (%)	Difference (%)
Age			
18–34	35.5	32.6	+2.9
35–54	39.2	30.6	+8.6
55+	25.3	36.8	−11.5
Gender			
Male	43.9	48.8	−4.9
Female	56.1	51.2	+4.9
Housing tenure			
Property owned outright	37.2	57.1	−19.9
Property owned with mortgage	62.8	42.9	+19.9
Housing type			
Flat, apartment or bungalow	12.3	29.6	−17.3
Detached house	29.1	17.9	+11.2
Semi-detached house	38.5	24.9	+13.6
Terrace house	20.2	27.6	−7.4
Number of occupants per property			
1	10.0	n/a[a]	
2	30.2	n/a	
3+	59.8	n/a	
Highest education level			
GCSE/O-Level or lower	21.7	n/a	
Vocational/NVQ	24.2	n/a	
Postgraduate qualification	21.4	n/a	
Degree or equivalent	32.7	n/a	
Annual income bracket (before tax)			
Less than £23,500	26.6	n/a	
More than £23,500 but less than £31,500	20.8	n/a	
More than £31,500 but less than £41,500	18.9	n/a	
More than £41,500 but less than £62,500	21.7	n/a	
More than £62,500	12.1	n/a	
Location			
South West and Wales	12.5	13.4	−0.9
Midlands and East of England	25.7	26.2	−0.5
South east and London	27.5	27.2	+0.3
North of England and Scotland	34.2	33.0	+1.2
Area type			
Inner City or industrial	8.9	n/a	
Suburban	52.1	n/a	
Urban	21.6	n/a	
Rural	17.4	n/a	

[a] n/a denotes the decision to exclude these variables when setting quotas, therefore population data is not reported here.
Source: Authors' compilation based on [377–379].

Appendix B. Descriptive statistics

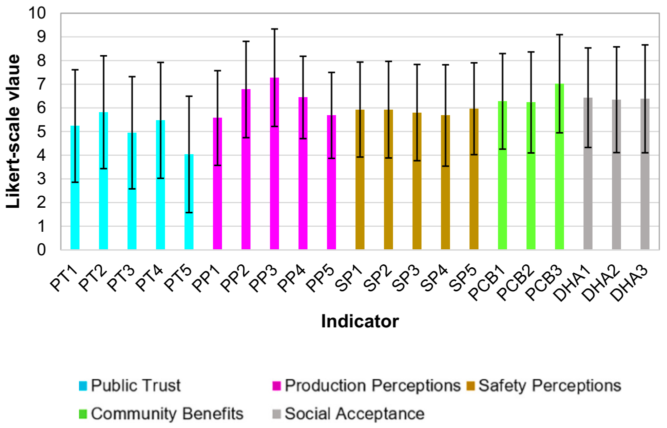

Fig. A1. Constructs measured on an eleven-point Likert scale.

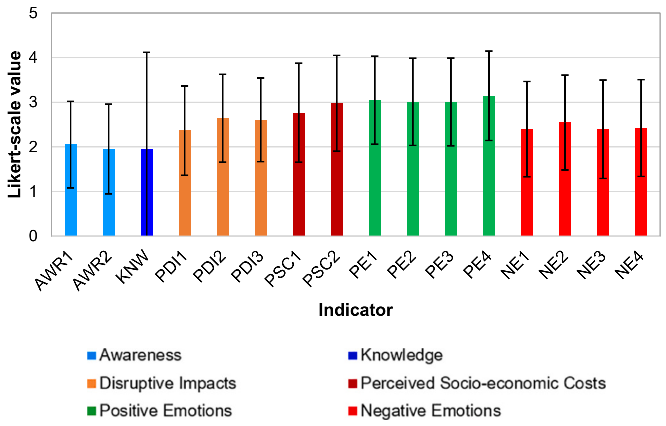

Fig. A2. Constructs measured on a five-point Likert scale.

Appendix C. Results for establishing discriminant validity

Traditionally, the Fornell Larcker criterion [380] has been used to assess discriminant validity, wherein each construct's AVE is compared to the squared inter-construct correlation of its own construct and all other (reflectively) measured constructs [48]. Indicators should load more strongly on their intended constructs than on other constructs to support discriminant validity [264], as illustrated in Table A2.

Following the critique of Henseler et al. [381], the heterotrait-monotrait (HTMT) ratio of correlations has been widely adopted as a more robust measure of discriminant validity [382], given its additional levels of sensitivity and specificity [383]. Discriminant validity is established when values fall below 0.85 for each construct, or below 0.90 when constructs share conceptually similarity [381]. HTMT values fell below the more conservative value of 0.85, thereby establishing discriminant validity for each construct (see Table 3).

Table A2
Fornell Larcker results for assessment of discriminant validity.

	AWR	PCB	PDI	KNW	NE	PSC	PE	PP	SP	DHA	ST
AWR	0.910										
PCB	0.091	0.849									
PDI	0.031	−0.164	0.821								
KNW	0.479	0.076	0.065	1.000							
NE	0.066	−0.233	0.412	0.102	0.846						
PSC	0.054	−0.341	0.284	0.138	0.427	0.887					
PE	0.248	0.449	−0.134	0.277	−0.088	−0.203	0.859				
PP	0.208	0.536	−0.154	0.216	−0.212	−0.280	0.353	0.760			
SP	0.075	0.549	−0.027	0.129	−0.123	−0.130	0.363	0.351	0.868		
DHA	0.166	0.677	−0.299	0.152	−0.351	−0.360	0.552	0.601	0.477	0.930	
ST	0.193	0.452	−0.122	0.225	−0.075	−0.061	0.383	0.407	0.436	0.545	0.803

Appendix D

Table A3
Assessment of constructs at the dimensional level.

Construct dimension	β coefficient	t-statistic	ρ-value	f^2	Result
Cognitive[a]	0.014	0.875	0.413	0.001	Rejected
Social capital[b]	0.198	10.207	<0.001	0.079*	Accepted
Environmental attitude[c]	0.214	10.897	<0.001	0.086*	Accepted
Risk perception[d]	0.075	4.167	0.002	0.013	Accepted
Cost-benefit appraisal[e]	0.167	7.775	0.001	0.059*	Accepted
Affective response[f]	0.178	10.462	<0.001	0.069*	Accepted

[*] Small effect (i.e. >0.02).
[a] Calculated as the mean value of β coefficients for AWR and KNW.
[b] Reflected by the β coefficient of ST.
[c] Reflected by the β coefficient of PP.
[d] Calculated as the mean value of β coefficients for SP and PDI.
[e] Calculated as the mean value of β coefficients for PSC and PCB.
[f] Calculated as the mean value of β coefficients for PE and NE.

Appendix E

Table A4
Comparison of PLS-SEM and CB-SEM.

Criteria	PLS-SEM	CB-SEM
Method focus	• Prediction-oriented	• Parameter-oriented
Method approach	• Variance-based	• Covariance-based
Method paradigm	• Causal-predictive: employs the coefficient of determination (R^2) to estimate the proportion of total variance explained	• Causal-explanatory: employs the coefficient of determination (R^2) to estimate the proportion of common variance explained
Method assumptions	• Soft-modelling approach with flexibility: predictor specification (non-parametric)	• Rigorous assumptions: multivariate normal distribution (parametric)
Statistical objective	• Maximising the variance explained in a target construct by incorporating common, specific, and error variance into the modelling parameters	• Estimates model parameters that minimise the differences between the observed sample covariance matrix (calculated before the analysis) and the covariance matrix estimated after the revised theoretical model is confirmed
Parameter estimates	• Consistent as indicators and sample size increase (i.e. consistency at large)	• Consistent
Latent variable scores	• Explicit since a single latent variable score is always produced for each composite per observation	• Indeterminate since an infinite number of different sets of latent variable scores can potentially fit the model equally well
Epistemic relationship between a latent variable and its measures	• Supports formative or reflective mode	• Supports reflective indicators typically
Implications	• Optimised for predictive accuracy	• Optimised for parameter accuracy
Model complexity	• Large complexity, e.g. up to 100 constructs and 1000 indicators	• Small to moderate complexity (e.g. less 30-40 indicators)
Sample size recommendation	• Power analysis based on the portion of the model with the largest number of predictors. Typically, the minimum number of cases range from 30 to 100 cases	• Power analysis on specified model. Typically, a minimum number of observations range from 200 to 800.

Source: Authors' design based on [70,264,384,385].

Appendix F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103437.

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