

Towards a unified theory of domestic hydrogen acceptance: An integrative, comparative review

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ABSTRACT

Hydrogen energy technologies are envisioned to play a critical supporting role in global decarbonisation. While low-carbon hydrogen is primarily targeted for reducing industrial emissions, alongside decarbonising parts of the transport sector, environmental benefits could also be achieved in the residential context. Presently, gas-dependent countries such as Japan and the United Kingdom are assessing the feasibility of deploying hydrogen home appliances, as part of their national energy strategies. However, prospects for the transition will hinge on consumer acceptance, alongside an array of other socio-technical factors. To support potential ambitions for large-scale and sustained technology diffusion, this study advances a Unified Theory of Domestic Hydrogen Acceptance. Through an integrative, comparative literature review targeting hydrogen and domestic energy studies, the paper proposes a novel Domestic Hydrogen Acceptance Model (DHAM), which accounts for the cognitive and emotional dimensions of human perceptions. Through this dual interplay, the proposed framework can increase the predictive power of hydrogen acceptance models.

1. Introduction

Following several decades of visions and forecasts [1–4], hydrogen is increasingly viewed as a potentially critical energy carrier for supporting a more sustainable global economy [5–8]. While the global potential of hydrogen remains undetermined [9–11] and subject to debate [12, 13], the historical record bears witness to the fuel's long, and at times controversial, history [14,15].

Hydrogen-fuelled energy technologies can be traced back to the early 19th century [16,17], however, present usage remains primarily limited to the industrial sector [18]. As documented by Ajanovic [19], hydrogen fuel cell vehicles (HFCVs) have struggled to penetrate national markets within recent decades, leading to limited global diffusion [20,21]. According to the International Energy Agency (IEA), battery electric vehicles (BEVs) currently outnumber HFCVs more than 350-fold, with market forecasts suggesting this gap could grow exponentially [22]. As a result, some analysts have asserted that HFCVs have already missed their opportunity to compete with alternative technologies for sustainable road transport [23,24].

The lack of market growth for HFCVs presents a cautionary tale for deploying and scaling up other hydrogen energy technologies, such as hydrogen-fuelled appliances for domestic space heating, cooking, and

hot water [25–27]. The feasibility of introducing low-carbon 'hydrogen homes' [28] has been explored since at least the early 2000s [29–31]. Notably, Japan emerged as a frontrunner following its early vision for developing a hydrogen-based energy society [31,32], as discussed by Aki et al. [29] in the context of a 'regional hydrogen energy interchange network' among consumers of hydrogen, heat, and electricity in residential areas.

Currently, the buildings sector accounts for approximately 39% of process-related greenhouse gas (GHG) emissions globally and around one-third of final energy demand [33–35]. Prioritising a reduction in residential carbon emissions has been stressed in recent forecasts from the IEA [36–38] and other entities [39,40] including the World Energy Council [41], with growing emphasis in both the European [42] and UK context [43,44]. In response, scholars have discussed the pressing need for transitioning towards net-zero energy buildings, realised through a shift to renewable or low-carbon energy sources and technologies, efficiency gains, and demand-side management [35,45].

Alongside Japan, other countries [36,38,41] including Australia [46, 47], Germany [48,49], the Netherlands [50], and the United Kingdom (UK) [51,52] are exploring the feasibility of deploying technologies to support residential decarbonisation. However, the hydrogen technology innovation system (TIS) remains at the formative phase [53,54], as reflected by demonstration projects [55,56] and local trials for hydrogen

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Nomenclature			
AWR	Awareness	MM	Motivational Model
BEVs	Battery electric vehicles	NA	Negative Affect
CAT	Consumer Acceptance of Technology	NAM	Norm Activation Model
CB-SEM	Covariance-Based Structural Equation Modeling	OK	Objective knowledge
CCS	Carbon capture and storage	PA	Positive Affect
CPB	Comprehensive Perceived Benefits	PBC	Perceived behavioural control
CPC	Comprehensive Perceived Costs	PEOU	Perceived ease of use
CPR	Comprehensive Perceived Risks	PLS-SEM	Partial Least Squares Structural Equation Modeling
CTAF	Comprehensive Technology Acceptance Framework	PU	Perceived usefulness
C-TAM-TPB	Combined TAM and TPB	RT	Rational Thought
DH-ACPT	Domestic Hydrogen Acceptance	SCT	Social Cognitive Theory
DH-ADPT	Domestic Hydrogen Adoption	SEM	Structural Equation Modelling
DHAM	Domestic Hydrogen Acceptance Model	SETA	Sustainable Energy Technology Acceptance
DoI	Diffusion of Innovation	SK	Subjective Knowledge
DTPB	Decomposed Theory of Planned Behaviour	SLR	Systematic Literature Review
EP	Environmental Perceptions	SP	Safety Perceptions
ER	Emotional Response	SRT	Social Representation Theory
FP	Financial Perceptions	ST	Social Trust
5D-DHAF	Five Dimensions of Domestic Hydrogen Acceptance Framework	TAM	Technology Acceptance Model
HFCVs	Hydrogen fuel cell vehicles	TIS	Technology innovation system
HFSs	Hydrogen fuelling stations	TP	Technological Perceptions
IBM	Integrated Behavioural Model	TPB	Theory of Planned Behaviour
IEA	International Energy Agency	TRA	Theory of Reasoned Action
IM	Integrative Model	TSA	Triangle of Social Acceptance
IS	Information System	UK	United Kingdom
IT	Information Technology	UTAUT	Unified Theory of Acceptance and Use of Technology
MIS	Management Information Systems	VAM	Value-Based Adoption Model
		VBN	Value-Belief-Norm
		VICE	Value-Innovation-Congruence

homes across parts of the UK [57,58]. Accordingly, the UK government is set to take a policy decision on the role of hydrogen in the residential sector by 2026 [51], which may accelerate the TIS for the wider national hydrogen economy [59].

During the formative phase of the technology cycle [60], new innovations must overcome a wide range of socio-technical barriers [59, 61] to bypass risks of non-adoption [62,63] or limited scaling up [64], as currently reflected by the low penetration of heat pumps within the UK market [65]. Consumers may resist technological change due to their belief structures, socio-cultural traditions, or personal behaviours, resulting in a state of resistance and rejection, as opposed to receptivity and acceptance [66–68]. Notably, the global diffusion of sustainable residential energy technologies, such as smart heating and smart meters, remains at a nascent stage [69]. Growth rates have lagged policy and market expectations due to multiple social and behavioural barriers [70–72]. Such barriers have counteracted the potential for low-carbon technology diffusion via a consumer-driven demand-pull effect in countries such as Germany [69].

Three decades ago, Herbig and Day [73] outlined the need “to ascertain the acceptability and eventual usability of the technology, innovation, or product before the dollars are invested to develop it.” Similarly, Dunphy and Herbig [74] emphasised how “the most successful innovations combine feasible technological bases, entrepreneurial skills, and knowledge of the needs and wants of the customers.” Within the “innovation triumvirate,” Dunphy and Herbig [74] argued that the most important ‘ingredient’ is ‘customer need’:

Businesses need to understand the reasons behind customer acceptance or rejection in order to become more efficient in their development efforts, and to recognise ways to improve competitiveness and profitability.

Despite this long-held argument among technology acceptance and marketing researchers [75–78], and its direct implications for the

potential uptake of low-carbon energy appliances [72,79], “the acceptance criteria” of residential consumers remains underexplored in the literature [80] and largely overlooked by policy makers. Notably, several latent dimensions underpinning attitudinal and behavioural energy acceptance are yet to be explored in-depth [81], especially in the context of domestic hydrogen technologies [27,28,58,82].

Although efforts are underway to increase understanding of hydrogen perceptions [28,83], the extant literature provides limited insights as to the validity of identified acceptance constructs [82]. To address this knowledge gap, theory development requires clear identification of the relationships between variables of interest [84], reflecting the notion that hydrogen acceptance studies should be rooted in strong conceptual justification and robust explanation [82]. In response, this integrative, comparative review is grounded in the following rationale: accelerating and sustaining momentum towards realising visions for low-carbon homes will entail developing a better understanding of consumer acceptance [85,86].

To date, researchers are yet to formally codify the dimensions of domestic hydrogen acceptance at the construct level. Given the pronounced knowledge gap, a flexible research approach is needed to advance theoretical understanding; mirroring Huijts’ [87] strategic decision to examine the social acceptance of hydrogen fuelling stations (HFSs) and carbon capture and storage (CCS) in parallel. Following the premise of Ventakesh et al.’s [88]. Unified Theory of Acceptance and the Use of Technology (UTAUT) and subsequent contributions such as the Consumer Acceptance Technology (CAT) model [89], the aim of this study is to develop a Unified Theory of Domestic Hydrogen Acceptance.

This objective is delivered through a three-stage approach, reflecting a systematic analysis grounded in theoretical, methodological, and empirical rigour [90]. Following this introduction and a description of the methodology, the first stage of the review involves a multi-decadal synthesis of theoretical developments in the field of technology

acceptance. This initial stage informs the boundaries for analysis within the subsequent integrative, comparative review focused on hydrogen technologies and domestic energy technologies. In the final stage, previous research strands are synthesised to provide the critical foundations for developing a Domestic Hydrogen Acceptance Model (DHAM). The study concludes by reflecting on research opportunities for advancing the DHAM.

2. Material and methods

The applied methodological framework adheres to the recommendations developed by Sovacool et al. [90], advocating for specific “codes of practice” to support “appropriate methods and research design,” wherein theoretical, methodological, and empirical rigour are upheld [91–93] to support transformative research [94,95].

Broadly, the review components of this study organise, integrate, and assess prior research to identify “relations, contradictions, gaps, and inconsistencies” within the literature [96]. Firstly, the paper undertakes a narrative review of key theoretical developments in the technology acceptance literature over the last six decades, leading to a subsequent systematic literature review (SLR), which is grounded in an integrative, comparative approach.

SLR extensively summarises scholarly literature by identifying, selecting, analysing, and synthesising relevant evidence [97,98]. Grounded in objectivity and reproducibility [90,99], SLR promotes “context-sensitive research” to develop a more comprehensive “knowledge stock” [100]. SLR may include qualitative as well as quantitative evidence [90,100], whereas meta-analysis involves applying statistical techniques (i.e. meta-regression) to synthesise quantitative evidence from several datasets,¹ which are collected via SLR [98,99,101,102].

This analysis implements a novel approach by integrating findings from two distinct energy acceptance literatures, namely, hydrogen energy systems and technologies, and domestic energy technologies. Firstly, results on hydrogen acceptance ($N = 33$) are presented, highlighting limited engagement with domestic hydrogen technologies for heating and cooking ($N = 6$). In response, a subsequent review is undertaken to bridge the knowledge gap on domestic hydrogen acceptance, whereby the focus is shifted to a range of domestic energy technologies ($N = 42$), including solar PV and solar water heaters, smart meters and smart grids, energy-efficient appliances, and low-carbon heating.

Firstly, both datasets are analysed independently to derive insights across four areas: relationships between keywords via bibliometric analysis; scholarly engagement with established acceptance theories; specific interactions with different dimensions of social acceptance (attitudinal, behavioural, community, market, and socio-political acceptance) [58]; and lastly, prevalence of operationalising different acceptance constructs within empirical analyses. Foremost, each acceptance construct appeared across both the hydrogen energy and domestic energy datasets at a suitable frequency to support both individual and comparative analysis.

Subsequently, the findings on hydrogen acceptance and domestic energy acceptance are synthesised to develop a Unified Theory of Domestic Hydrogen Acceptance, which can serve as a baseline model for future research. The comparative assessment introduces a more substantive meta-analytical component to this review, alongside the quantitative assessment of social acceptance via the Five Dimensions of Domestic Hydrogen Acceptance Framework (5D-DHAF) [58]. The approach mirrors previous efforts to unpack linkages between technology adoption predictors [79,103], albeit without the application of robust statistical methods [102,104], which may be incorporated into subsequent analysis.

¹ Usually via a quantitative index of effect size [99], as recently conducted by Neves et al. [79] in this context.

In summary, the applied research methodology follows a three-stage process consisting of the following outputs: (1) a historical, narrative review of theoretical developments in the technology acceptance literature over the last six decades; (2a) SLR of hydrogen acceptance studies since 2008; (2b) SLR of domestic energy acceptance studies since 2011²; (2c) comparative analysis of hydrogen and domestic energy acceptance studies; and finally, (3) proposing a Domestic Hydrogen Acceptance Model (DHAM) based on the unification of previous research strands (see Fig. 1).

2.1. Materials on technology acceptance

The starting point for this investigation involved a Scopus keyword search for “technology acceptance theories” using article title, abstract, and keywords as the filter. The search returned 135 results when limited to journal articles in English. In total, nine studies – composed of seminal and more recent contributions – were reviewed in detail to establish a foundational knowledge base on technology acceptance for undertaking a historical, narrative review.

The selected articles supported retrieval of multiple seminal studies through snowballing. The snowballing technique involves identifying materials of interest sourced from reviewed studies within the initial search, which in this case was limited to a small sample ($N = 9$). Both forward snowballing (i.e. identifying citations of a selected article) and backward snowballing methods (i.e. accessing reference lists) [105,106] were employed to substantiate the sub-sections composing the theoretical review.

Historically, seminal contributions to the acceptance literature have engaged primarily with information systems and technologies [88,107,108]. In addition to distilling the theoretical foundations of this research stream, the narrative review component maps recent contributions [58,109,110] focusing on the social acceptance of low-carbon energy technologies [111]. Consequently, the analysis reflects progression from the organisational context focused on computing technologies, to the consumer context engaging with domestic energy applications. Lastly, efforts to advance integrated theories of energy acceptance are also acknowledged.

While the review builds significantly on prior summaries [112–114] and can therefore serve as a stand alone as a historical analysis, the main motivation is to lay the necessary groundwork for systematically evaluating empirical engagement with acceptance constructs across energy studies to develop the DHAM.

2.2. Studies on hydrogen energy technology acceptance

Prior reviews on hydrogen acceptance provide critical insights regarding developments in the literature within the last two decades. The SLR conducted by Emodi et al. [83] retrieved 43 studies for the period 2008–2020 after implementing a stringent search and exclusion criteria to an inclusive keyword search.³ Considering the final objective of this analysis, it is noteworthy that only five studies focused on the domestic energy context, even though grey literature reports were included in the review [83]. Subsequently, Scovell [82] conducted a narrative review of 27 quantitative studies for the period 2005–2021 [82],⁴ wherein 15 of the results overlapped with the analysis conducted

² In addition to one study from 1993 [393] which is included for illustrative purposes and more thorough contextualisation.

³ Emodi et al. [83] applied the following search string: “consumer acceptance” OR “community acceptance” OR “household acceptance” OR “social acceptance” OR “public acceptance” AND “hydrogen”.

⁴ Scovell [82] implemented a keyword search with “hydrogen” and several combination terms: acceptance, acceptability, attitude, perception, belief, opinion, intention, behaviour, and behavior.

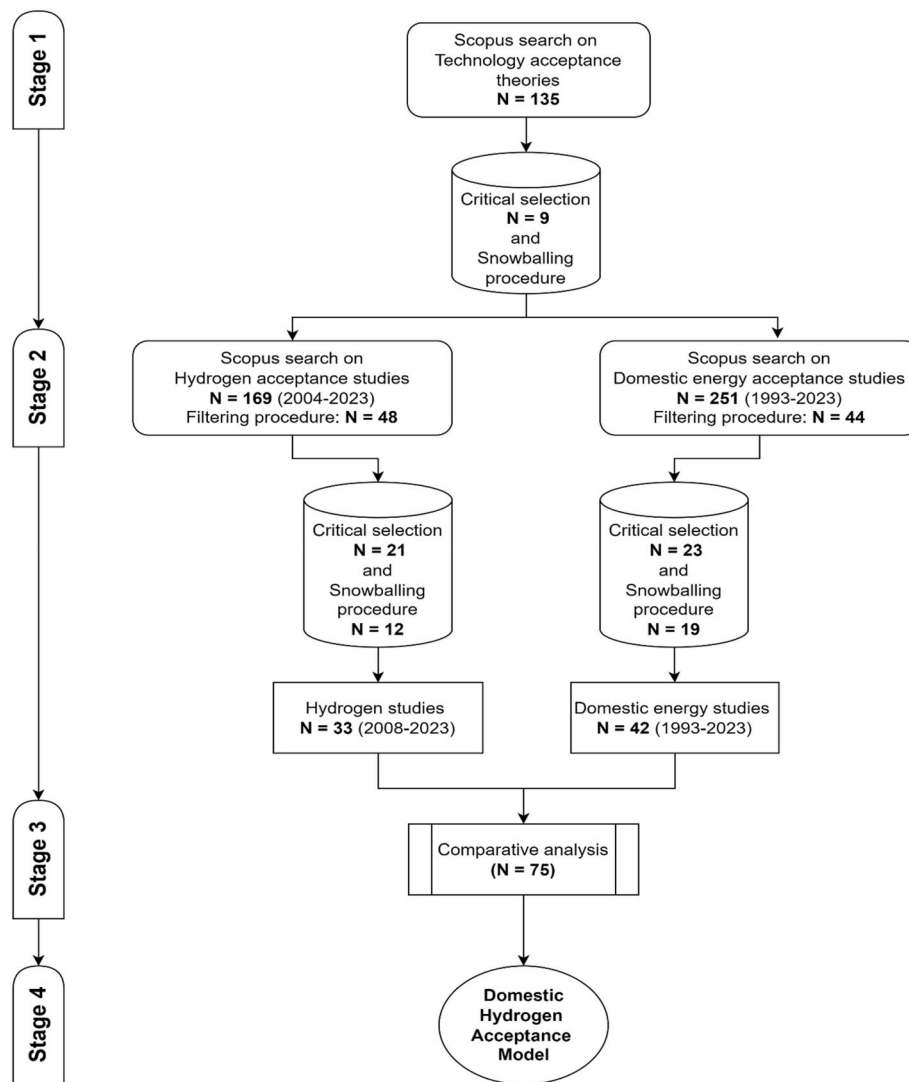


Fig. 1. Research stages and selection protocols for reviewed studies.

by Emodi et al. [83].⁵ Mirroring prior trends, most studies focused on public perceptions of HFCVs or HFSs [82], which has been further acknowledged in follow-up research [115].

Gordon et al. [28] conducted a narrative review on domestic hydrogen acceptance using a range of databases and keyword searches, which recorded 17 results for the period 2017–2022. However, seven of the retrieved studies provided a partial focus on domestic hydrogen, as opposed to an exclusive focus. Furthermore, among the sample, only six studies were sourced from the academic literature, representing public perceptions in the UK [26,27], Australia [116], and parts of Europe [117–119].

Consequently, existing reviews on hydrogen acceptance reflect an underlying deficiency in available academic studies, especially in the context of residential consumers. Moreover, this synopsis suggests the need for a more comprehensive and up-to-date review to consolidate previous findings. Notably, each of the identified reviews present somewhat disparate search results and research angles.

For the purposes of this analysis, the review of Scovell [82] is the most instructive entry point. Each of the studies analysed by Scovell [82] incorporated constructs from the Sustainable Energy Technology

Acceptance (SETA) model [109], leading to a quantitative comparison of scholarly engagement with the following aspects of hydrogen acceptance: perceived effects (perceived risks/safety concerns; perceived benefit/value/usefulness; perceived cost); awareness; knowledge (objective and subjective); experience; social trust; fairness; affect (i.e. emotional response); personal norm; and problem perception/awareness [82].

Acknowledging the research trajectory set by Scovell [82], this study aims to extend the evidence base by reviewing additional studies and applying a new research lens, whereby selected acceptance constructs are further demarcated according to different dimensions such as psychological, technological, environmental, and financial.

To optimise the retrieval of available hydrogen acceptance studies, the following keyword search was conducted in Scopus, set to article titles, abstracts, and keywords: “hydrogen” AND “public perceptions” OR “public attitudes” OR “social acceptance” OR “consumer acceptance” OR “technology acceptance”. The search returned 169 results for journal articles in English for the period 2004–2023. Following a screening of all titles and abstracts, 48 studies were retained for further analysis. However, only 21 studies qualified for inclusion in the review, whereby all requirements were adequately met for the purposes of analysing theoretical approaches, engagement with social acceptance dimensions, and application of acceptance constructs (see Table S1 and Table S2).

⁵ Four studies reviewed by Scovell [82] predated 2008 [305,322,394–396], while seven additional studies were included for the period 2008–2020 [128, 213,253,257,262,397,398], with one sourced from 2021 [273].

Studies were excluded for lacking primary data analysis [28,120,121], or otherwise failing to develop a conceptual framework [122,123] or operationalise an empirical model [124–126]. Furthermore, analyses focused on stakeholder perceptions were discarded [127,128] to preserve a focus on public perceptions. Additionally, cross-country comparative studies [117,118] and longitudinal analyses [129,130]⁶ were filtered out to help streamline comparative results within the integrative review. Finally, snowballing methods were applied to expand the evidence base, resulting in the retrieval of 12 additional studies, with seven results sourced from 2020 to 2023 (see Table S1).

2.3. Studies on domestic energy acceptance

The second stage of the SLR involved retrieving international studies on domestic energy acceptance. The following keyword search was undertaken in Scopus, scanning article titles, abstracts, and keywords: domestic energy acceptance OR domestic technology acceptance OR residential energy acceptance, AND theoretical OR theory OR conceptual OR concept OR model.⁷ The search returned 437 documents including of 251 journal articles in English, which were eligible for screening. Following a review of all titles and abstracts, 44 studies with an explicit focus on energy technology acceptance were included for further assessment. Following this screening stage, 23 studies qualified for inclusion in the final review (see Tables S3 and S4).

Foremost, to ensure the underlying objectives of the literature review could be fulfilled, studies lacking an explicit theoretical framework were discarded (e.g. [131–133]). Additionally, only studies with primary data were included, although meta-analyses such as Schulte et al. [134] and Ganvir and Kalita [135] provided scope for retrieving additional results through snowballing. Furthermore, articles concentrated on technologies operating beyond the household environment such as electric vehicles [136] and battery storage systems [137], or without a consumer-centric focus [138], were also excluded. Similarly, the filtering process removed studies focused on the interaction between different technologies [139] or otherwise restricted to off-grid, rural locations [140].

Finally, cross-country comparative analyses were excluded from the review [141–143]; except for the study of Karytsas et al. [144] which presents similar findings across three countries (Greece, Portugal, and Spain). Through snowballing, an additionally 19 studies were retrieved which satisfied the required criteria (see Table S4), leading a more extensive sample size (N = 42).

3. Theoretical foundations of domestic energy acceptance

This section examines theoretical contributions to the technology and energy acceptance literature since the 1960s, which are subsequently discussed within the context of the domestic hydrogen transition. The first sub-section draws on critical results from a targeted keyword search in Scopus, as reported in the methods. The next three sub-sections follow a broadly chronological order, reflecting historical developments in the technology acceptance literature. The penultimate sub-section forecasts the contribution of this paper by outlining integrated theories of energy acceptance, while the final sub-section summarises the main findings.

⁶ Achterberg [399] was retained given its ease of interpretation compared to studies conducted in Japan [129,130] covering multiple time periods.

⁷ A parallel keyword search was undertaken in Scopus, which returned only 166 journal articles: Social acceptance OR technology acceptance AND domestic energy technologies OR residential energy appliances OR residential energy technologies. After screening both sets of results for valid studies and tracking any duplicates results, the larger search was selected.

3.1. Scopus results for technology acceptance theories

Following the Scopus search for “technology acceptance theories” and filtering process (N = 135), nine studies – composed of seminal and more recent contributions – were reviewed in detail. This selection provided sufficient scope to establish a foundational knowledge base on technology acceptance for undertaking a historical, narrative review, as detailed in Supplementary Note 1 (see SN1).

The earliest study, as well as the most cited, was traced to Agarwal’s and Karahanna’s [145] article on ‘cognitive absorption and beliefs about information technology usage’. Critically, the opening paragraph of the paper cites a range of seminal contributions, including “innovation diffusion theory [146,147], the technology acceptance model (TAM; [107,148], the theory of reasoned action (TRA; [149,150], and the theory of planned behaviour (TPB [151–153])”.

The next most cited study corresponded to Komiak’s and Benbasat’s [154] seminal work, which applied partial least squares structural equation modelling (PLS-SEM) to examine “the effects of perceived personalisation and familiarity on cognitive trust and emotional trust on consumer intention to use a web-based, product-brokering recommendation agent for electronic commerce.” Notably, Benbasat and Moore [155] extended Rogers DoI in the early 1990s, before integrating DoI and the Theory of Reasoned Action (TRA) into subsequent work on technology acceptance [156]. Next, Scopus retrieved the seminal study of Chau and Hu [157], which employed covariance-based structural equation modelling (CB-SEM) to compare the TAM, TPB, and a decomposed TPB model in the context of telemedicine technology acceptance in Hong Kong.

The remaining Scopus results were selectively considered [158] to extract additional insights. Notably, the seventh most cited study presents a more recent contribution wherein Chao [159] applied an extended version of Ventakesh et al.’s [88] UTAUT to examine the factors predicting students’ behavioural intentions toward using mobile learning in Taiwan, which was explored using PLS regression.

Foremost, the eighth most cited study further motivates the current contribution, as reflected by the 2007 publication of Kulviwat et al. [89]: “Toward a unified theory of consumer acceptance technology.” The study [89] examined user perceptions of ‘high-technology innovation’ (Microsoft’s Pocket PC operating system) in the organisational setting by merging the TAM and a previously unrelated model, in Mehrabian’s and Russell’s Pleasure, Arousal, and Dominance paradigm of affect [160], thereby linking traditional acceptance constructs to emotional response.

In addition to the five highly cited studies described, four recent articles were examined (see Table 1) before saturation was reached in terms of retrieving a foundational knowledge base. As a result, the

Table 1
Key results from Scopus search on technology acceptance.

Study	Focus and context	Theoretical lens
Juric and Lindenmeier [161]	Influence of passive and active innovation resistance towards smart-lighting products in the German context (N = 653)	Extended UTAUT model implementing performance expectancy, social pressure, and compatibility
Meyer-Waarden [162]	Acceptance and resistance factors of artificial intelligence-based smart homes among consumers in France, Germany, and China (N = 301)	Merged the UTAUT with a trust-based model
Alshami et al. [163]	Consumer acceptance of COVID-19 Digital Contact Tracing Apps in Malaysia (N = 150)	UTAUT
David et al. [164]	Bibliometric analysis of fourth industrial revolution (4IR) technologies in the context of the water, energy, and food nexus for sustainable security	DoI and TAM

Table 2
Overview of seminal theories and models on technology acceptance and human behaviour.

Seminal theory	Author(s) and Year of publication	Theoretical grounding	Constructs or relationships underlying theoretical model
Diffusion of Innovation (DoI) Theory	Rogers [147] 1962	Several theories of organisational life from across the social sciences ^a	<ul style="list-style-type: none">• Relative advantage• Compatibility• Complexity• Trialability• Observability^b
Theory of Reasoned Action (TRA)	Fishbein and Ajzen [150] 1975	Social psychology (information integration theory; cognitive dissonance theory)	<ul style="list-style-type: none">• Attitude towards behaviour^c and subjective norms^d predict behavioural intention, which in turn predicts actual behaviour
Theory of Planned Behaviour (TPB)	Ajzen [173] 1985	TRA	<ul style="list-style-type: none">• Attitude towards behaviour, subjective norms, and perceived behavioural control (PBC)^e predict behavioural intention, which in turn predicts actual behaviour
Technology Acceptance Model (TAM)	Davis [170] 1989	TRA ^f	<ul style="list-style-type: none">• Perceived usefulness (PU) moderates the impact of perceived ease of use (PEOU) and attitudes towards use, and has a direct effect on attitudes towards use and intention to use^g
Unified Theory of Use and Acceptance of Technology (UTAUT)	Venkatesh et al. [88] 2003	Eight established models of technology acceptance ^h	<ul style="list-style-type: none">• Performance expectancy• Effort expectancy• Social influence• Facilitating conditions

^a Anthropology, early sociology, rural sociology, education, public health and medical sociology, communication, marketing, geography, and general sociology.
^b Alternatively, some authors use ‘expected’ (e.g. risks), instead of perceived, as a proxy for potential technology adoption [215].
^c i.e. Behavioural beliefs (beliefs about the likely consequences of the behaviour).
^d i.e. Normative beliefs (self-perception of group norms concerning the behaviour).
^e i.e. ‘control beliefs (self-perception of intention and ability to perform the behaviour).
^f Grounded in Management Information Systems (MIS) attitudes research, MIS laboratory research, Human-computer Interaction (HC) laboratory research.
^g PU and PEOU can be equated with the relative advantage and compatibility attributes formulated in the DoI model.
^h DoI, TRA, TPB, TAM, C-TAM-TPB, Social Cognitive Theory (SCT), the Motivational Model (MM), and Model of PC Utilisation.

selected studies provided inclusive coverage of several established acceptance theories, wherein DoI emerged as a starting point for charting historical developments.

3.2. From diffusion of innovation theory to the Unified Theory of acceptance Use of Technology

Developed in the early 1960s, Everett Rogers’ Diffusion of Innovation (DoI) Theory marks a seminal moment in the technology acceptance literature [147]. DoI theory posits that “the gradual adoption of an innovation in a market segment or in a society” [165] can be seen as “the process by which an innovation is communicated through certain channels over time among the members of a social system” [147].

The framework provides a powerful foundation for assessing the early stages of technology acceptance (see SN1), whereby consumers firstly gain exposure to the product or innovation, before attaining a degree of knowledge and awareness to inform their attitudes and adoption decision [166,167]. Rogers’ framework has since been applied to a range of contexts [168,169] and features prominently in subsequent theories of technology acceptance, such as the TAM [170] and UTAUT [88,171]. Additionally, the key constructs proposed within the DoI model (see Table 2) are generalisable to emerging low-carbon technologies [172], such as hydrogen home appliances [25–27]. Critically, perceived technology attributes such as relative advantage have proved a significant predictor of consumer acceptance in the context of sustainable technology adoption [79].

Following the contribution of Rogers [147], the Theory of Reasoned Action (TRA) [150] and its successor, the Theory of Planned Behaviour (TPB) [173]⁸ are cornerstones of socio-psychological approaches to human decision-making and behaviour [174]. Both theories adhere to the class of “expectancy-value models,” which theorise that consumer behaviour is shaped by beliefs related to how a given product performs and meets specific needs [175].

Consequently, TRA and TPB which have gained prominence among

researchers in fields such as social, health, and environmental psychology [176,177]. Notably, social scientists have critiqued and compared both models (TRA and TBP) [178,179], added constructs to test new hypotheses [180,181], and applied these methods to different cases of technology acceptance and environmental behaviours [175,182–185].

Alongside the TRA and TPB, Stern et al.’s [186] Value-Belief-Norm (VBN) theory of environmentalism has been applied to explain consumer attitudes towards both environmental and energy policies [187]. Comparing the TPB and VBN models (see SN1), Kaiser et al. [188] describe the former theory as “being grounded mainly in self-interest, whereas the VBN is “moral-norms and values-centred” (i.e. normative).⁹ Accordingly, scholars have integrated constructs from the NAM, TRA, and TPB to the study of environmental psychology [189–191] and renewable energy acceptance in various national contexts [192–197].

Following the TPB, Davis developed the TAM during the mid-1980s [198]; formalising the model in his seminal contribution to MIS Quarterly Journal [170], which hosts multiple seminal contributions to the field of technology acceptance [88,199,200]. The TAM examines acceptance of the use of information system and information technology innovations in the organisational context [201]. The main antecedents of the TAM are found in the TRA [202]. The TAM was subsequently revised by Venkatesh and Davis in 1996 [203]¹⁰ and further refined by the authors in 2000 (i.e. TAM2) [108], leading to the development of TAM3 by Venkatesh and Bala [204] in 2008,¹¹ as outlined in Fig. 2.

⁸ TPB added to TRA and has since also been expanded into the Integrated Behavioural Model (IBM) or Integrative Model (IM) [400].

⁹ Relatedly, the recently developed Value-Innovation-Congruence model of Emotional responses (VICE model) suggests that positive and negative emotions are reflected by the extent to which an innovation or technology is congruent with people’s core values [311,312].

¹⁰ The authors eliminated the attitudinal construct and moderating relationship between PU and PEOU.

¹¹ One of the notable augmentations of TAM also included the earlier hybrid model developed by Taylor and Todd [181], referred to as the Combined TAM and TPB (C-TAM-TPB). In parallel, Taylor and Todd [179] proposed the Decomposed Theory of Planned Behaviour (DTPB). Notably, Mathieson [401] provides an early comparison of TAM and TPB, prior to the development of the C-TAM-TPB.

Foremost, iterations to the TAM were motivated by the need to increase the predictive power of technology acceptance models.

Building on prior contributions [203,205], Venkatesh et al. [88] subsumed multiple constructs from established models of technology acceptance into a single framework (see Table 2). Mirroring developments in the tradition of TAM, Venkatesh et al. [200] extended the UTAUT in 2012 to analyse technology acceptance in the consumer context, as opposed to the organisational setting (i.e. UTAUT2).¹² Thereafter, Venkatesh and colleagues [171] proposed a ‘multi-level framework of technology acceptance’ which synthesised findings from existing UTAUT models and flagged key areas for future study. Other studies have further highlighted ways to link constructs from the UTAUT and DoI theory to better predict technology acceptance [206].

Subsequently, the UTAUT has been widely adopted as a baseline model to examine various applications beyond the IT sector [207], including a wide range of energy technologies [208–212]. Critical to the context of this study, researchers have demonstrated the applicability of UTAUT to examining household acceptance and adoption for smart meters and associated technologies [211,213] (see SN1). Furthermore, based on a review of the UTAUT literature, Billanes and Enevoldsen [208] identified ten influential factors impacting the acceptance and uptake of a range of smart energy technologies and other emerging applications.¹³ Overall, UTAUT-based models have been shown to outperform prior models such as the DoI, TRA and TPB, and TAM [214].

3.3. Sustainable energy technology acceptance model

A critical juncture in advancing the understanding of energy technology acceptance coincides the Doctoral thesis of Nicole Huijts [87].¹⁴ Huijts’ thesis explored social acceptance and consumer decision-making in the context of two emerging sustainable energy technologies, namely, HFSs and carbon capture and storage (CCS) [87]. This angle helped pave the way for subsequent studies, as literature on energy acceptance gained increasing traction within the last decade [212,216–218].

Huijts and colleagues [109] reviewed evidence from socio-psychological theories and empirical studies from the technology acceptance literature; proposing an integrated framework for examining consumer acceptance of sustainable energy technologies, such as wind farms, CCS, and hydrogen. The SETA framework¹⁵ has subsequently been described as “a universal and comprehensive model” of new energy technologies [219].

The SETA model, which has its antecedents in the TPB and NAM [220], includes 16 variables as predictors of ‘intention to accept’ a sustainable energy technology (see Table S5), which in turn predicts overall acceptance [109]. Notably, the SETA model also internalised the perspective of the Triangle of Social Acceptance (TSA) [110] by distinguishing between different types and scales of energy acceptance.

Numerous energy acceptance studies have adopted or extended the SETA framework to examine public perceptions and consumer attitudes [221–223]. For example, Lozano et al. [222] included several SETA variables when examining hydrogen acceptance in Australia.¹⁶ To quantify the impact of the SETA model [109] on energy acceptance

scholarship, a keyword search was performed in Scopus (all fields) for “sustainable energy technology acceptance,” which returned 541 journal articles in English for the period 2012–2022. The results of the search are displayed in Fig. S1, underscoring the sustained growth of the SETA model across leading energy journals.

3.4. The Triangle of Social Acceptance and the five dimensions of domestic hydrogen acceptance

Seminal contributions to the technology acceptance literature demonstrate the efficacy of synthesising traditional DoI theory with socio-psychological models of consumer behaviour, such as the TRA [224] or TPB [225,226], otherwise amalgamated under the UTAUT [207]. Within the renewable energy acceptance literature, researchers have likewise bridged the individual level of decision-making with wider socio-political and socio-economic factors, which can be seen to operate at the macro- or meso-level [58,110,227].

Wüstenhagen et al. [110] proposed a three-dimensional, multi-level framework of energy acceptance, composed of socio-political, market, and community acceptance. Socio-political acceptance operates at the macro- or national level [228], whereas market acceptance “operates at a meso-level between national politics and local communities” [229].¹⁷ Community acceptance is shaped by the degree to which local stakeholders are involved in and supportive of new energy plans or projects [110].

Similarly, the technology innovation systems (TIS) framework [230, 231] examines technology diffusion as part of an existing socio-technical system [232,233], which may be reshaped by interactions between multiple actors and stakeholders across different scales or levels [234–236]. Relatedly, Wilson and Dowlatabadi [174] describe how the ‘socio-technical regime’ – constituted by the interrelations between technology, society, and individuals – shapes the diffusion of domestic energy systems.

Reviewing developments in the tradition of renewable energy acceptance, Gordon et al. [58] argued that given its focus on community projects such as onshore wind farms, the TSA is less applicable to energy technology decisions made at the household or micro-level. In turn, the authors proposed the Five Dimensions of Domestic Hydrogen Acceptance Framework (5D-DHAF), which integrates attitudinal and behavioural acceptance as additional dimensions of social acceptance [58]. As described by Demski et al. [237], the 5D-DHAF provides a comprehensive approach for examining “potential socio-technical barriers to domestic hydrogen acceptance.”

In a similar vein to traditional technology acceptance models and behavioural theories, the 5D-DHAF posits that dimensions of socio-political, market, community, and attitudinal acceptance must be sufficiently aligned to facilitate behavioural acceptance; realised through the adoption of domestic hydrogen appliances, “established on grounds of cognitive, socio-political, and socio-cultural legitimacy” [58]. Mirroring other low-carbon alternatives [238] such as domestic micro-generation technologies [239], the adoption of hydrogen home appliances will ultimately rest on decisions made at the micro-scale by households and individual consumers [58].

3.5. Integrated theories of energy acceptance

Theoretical developments in the literature reflect the emergence and efficacy of combining multiple acceptance theories within analyses. Nevertheless, in 2007, Wilson and Dowlatabadi [174] observed that studies on domestic energy acceptance had broadly engaged with four

¹² UTAUT2 incorporated three new constructs (hedonic motivation, price value, and habit), alongside additional moderating variables (age, gender, and experience), with the model explaining 74% and 52% of the variance in consumers’ behavioural intention and technology use [200].

¹³ Knowledge; awareness; trust; social influence; policy; self-efficacy; compatibility; socio-demographic variables; perceived risk; and perceived enjoyment (i.e. hedonic benefits).

¹⁴ Sustainable Energy Technology Acceptance: a psychological perspective.

¹⁵ The authors refer to their model as the “Comprehensive Technology Acceptance Framework” (CTAF), but across the literature most authors refer to the SETA model, as confirmed within the Scopus search.

¹⁶ Affect, trust, safety, perceived effects (costs, benefits, and risks), and free-market support.

¹⁷ Social acceptance can also be interpreted as market acceptance ... we can learn from the literature on diffusion of innovation, which explains the adoption of innovative products by consumers through a communication process between individual adopters and their environment [110].

theoretical approaches: (1) neo-classical and behavioural economics; (2) DoI theory and attitude-based decision-making; (3) social and environmental psychology; and (4) sociology [240].

In their weight and meta-analysis of sustainable energy technologies carried out in 2022, Neves et al. [79] noted that most studies had either adapted or extended the TPB or TAM¹⁸ when developing conceptual approaches [79]. While more than a decade apart, both research groups [79,174] advocate for advancing integrated conceptual frameworks to better comprehend consumer perceptions and attitudes towards emerging energy technologies.

It has been shown that consumer preference for adopting domestic energy technologies is driven by a combination of cognitive and psychological factors, wherein rational and emotional parameters of decision-making interact [81]. Fundamentally, a highly “integrated perspective” is needed to examine domestic energy acceptance, which should account for “the interplay between knowledge, psychological and social factors” [241]. Hobman and Ashworth [241] further describe this perspective in terms of examining ‘cognitive, knowledge-based factors’, ‘belief-driven factors’, and ‘external, socially-derived variables’. Notably, Chadwick et al. [242] responded by constructing a framework of human influences on household adoption and rejection energy technology, rooted in understanding cognitive, social, affective, and behavioural influences, alongside contextual factors.¹⁹

As the literature has evolved, energy preferences and behaviours have been linked to a range socio-psychological determinants, cultural, and ethical factors [240,243]. Given the complexity of human behaviour and decision-making, a minority of scholars have responded to the call for a more integrated research approach, marking a gradual shift towards developing unified theories of domestic energy acceptance [174, 226,244–246]. For example, Bögel et al. [247] integrated approaches from psychology, innovation, and technology transition studies when examining attitudinal acceptance of hydrogen fuel cells in the European context. Furthermore, Elmustapha et al. [245] highlighted “the importance of combining theoretical notions from different academic traditions,” as reflected by results showing more predictive power and better model fit when testing an integrated model against individual components of the model.

While such contributions stand out for drawing on a wide range of theories from across the social sciences to support theoretical pluralism, the need for further exploration has been stressed in recent studies [79, 82]. Insightfully, in the context of systemic action research [248], Midgley [249] draws parallels to the underlying premise of linking theory and methods: “... given that different theories inform different methodologies and methods, *methodological* pluralism (drawing upon methods from different paradigms) becomes a useful partner to *theoretical* pluralism.”

3.6. Summary of technology acceptance theories

This narrative review has traced developments in theories of technology acceptance and consumer behaviour since the early 1960s, thereby linking together historic contributions, as well as more recent and emerging additions to the literature. Fig. 2 consolidates the discussion by visualising some of the key links between theories, documented according to their corresponding time-period.

The TAM built on Rogers’ DoI theory, as well attitudinal and behavioural insights developed in the TRA and TPB. Taken together, the DoI, TRA, and TPB (grey boxes) can be considered as the building blocks

of the technology acceptance literature, which emerged in earnest during the late 1980s and early 1990s; focusing on information systems in the organisational context through a primarily cognitive lens, which carried through into the 2000s [250].

Following the TAM, various iterations were made over the course of the next two decades (blue boxes), which moved towards a greater synthesis of acceptance factors and increased predictive power in models. Among these iterations, the UTAUT [88] is particularly noteworthy for its synthesis of prior concepts, while the UTAUT2 marked a critical shift towards engaging more directly with technology acceptance in the consumer context.

Subsequently, the TAM and UTAUT have been used in a wide range of case studies and contexts to examine “the influence of external variables on the user perspectives and usage intentions” towards different technologies [251], including consumer behaviour towards different energy technologies [252]. In parallel, the concept of social acceptance was gradually solidified in the literature throughout the 2010s following the contribution of Wüstenhagen et al. [110].

Alongside the TSA, the SETA model and 5D-DHAF (green boxes) can be categorised as a turning point in the literature, wherein scholars systematically applied previous insights on acceptance theories to the study of renewable energy innovation projects, sustainable energy technologies, and domestic hydrogen technologies, respectively. This parallel shift in focus, also reflected by the framing of the UTAUT2, has elevated the importance of examining social acceptance and consumer perceptions in the context of sustainable energy transitions [79,242].

Overall, reviewing theoretical developments in the technology and sustainable energy acceptance literatures highlights the scope for developing integrated, conceptual frameworks to increase the predictive capability of models and robustness of quantitative analyses.

4. Systematic literature review on energy acceptance

4.1. Hydrogen energy technology acceptance

The SLR on hydrogen energy acceptance, as supported by snowball sampling ($N = 33$), accounted for 20,655 respondents after removal of duplicate datasets ($M = 617.6$; $SD = 645.5$).²⁰ In total, when accounting for the devolved nations of the United Kingdom (England = 1, Scotland = 2), 12 countries are represented within the sample (see Table S2).

The highest number of studies originate from the Netherlands ($N = 7$) following several outputs from Huijts and colleagues [253], while emerging research groups in India [254,255] and the United Kingdom [26,256] were equally represented ($N = 4$), followed by Australia, Japan, and Taiwan ($N = 3$). Alongside Scotland, China and Germany are represented by two studies each, while Denmark and South Korea had a single study. Regarding research outputs from the Netherlands, it is noteworthy that various studies drew on different theoretical models and explored a range of causal relationships, even when the same datasets were analysed [221,253,257].

Consequently, the geographic distribution of hydrogen acceptance studies is dispersed, albeit highly concentrated around research hubs in Northern Europe, Asia, and Australia. Foremost, European studies present less relative diversity in terms of location and authorship. The observed trends reflect advancements in national hydrogen strategies, with all countries within the dataset (excluding Taiwan) having official policies or roadmaps for developing hydrogen-based energy systems. While it is beyond the scope of this integrative, comparative review to analyse policy and research developments in details [258–260], Fig. S3 affirms the linkages between these two areas.

The links between the retrieved studies were explored in VOSviewer [261], which returned 92 connected keyword items distributed across

¹⁸ Broadly, models are described in the literature as ‘extended TAM’ [223, 402] when rooted in the tradition of Davis, Venkatesh and colleagues, and ‘extended TPB’ [193,196] when grounded in the work of Fishbein and Azjen.

¹⁹ The study of Chadwick et al. [242] is additionally noteworthy for combining SLR, content and thematic analysis, and meta-regression techniques to consolidate the proposed framework.

²⁰ Huijts et al. ($N = 1214$) [221,253,257] and Gordon et al. ($N = 58$) [256, 271,272].

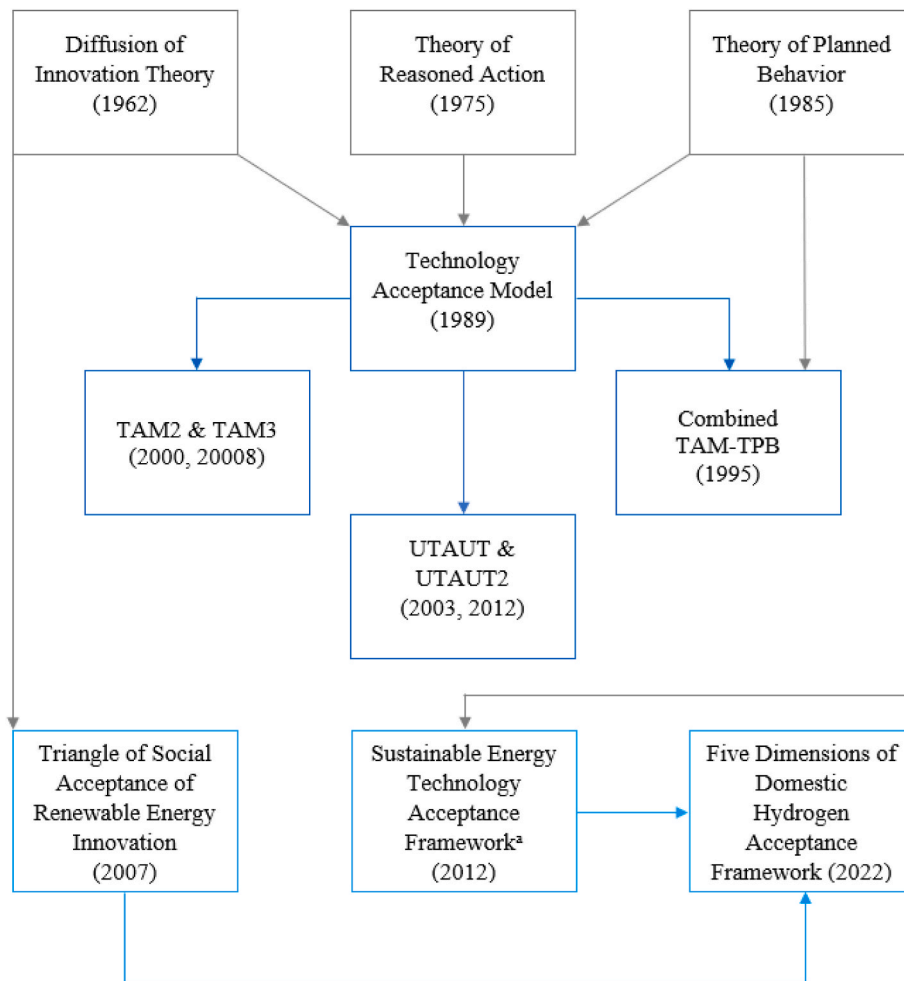


Fig. 2. Theoretical developments in technology and energy acceptance, 1962–2022.

^a In addition to TPB, the SETA Framework is derived from the Norm Activation Model (NAM).

12 clusters ($N = 112$, co-occurrence threshold set to 1). The largest cluster contains 13 items, capturing ‘social acceptance’ and ‘psychological factors’, thereby reflecting the attitudinal acceptance dimension. The second largest cluster ($N = 12$) includes ‘government policy’ and ‘policy interventions’, and ‘consumer behaviour’, corresponding to the socio-political and behavioural acceptance dimensions. Furthermore, the market and community acceptance dimensions emerge in different clusters, as highlighted by ‘hydrogen economy’ and ‘economics and management’, and ‘place attachment’, ‘energy justice’ and ‘community-led’, respectively. Within one of the smaller clusters ($N = 5$), different theoretical approaches also prevail, vis-à-vis the TPB, NAM, and TAM. Additionally, structural equation modelling is displayed as ‘SEM’ in the yellow cluster, as a representation of quantitative methods (see Fig. 3).

4.1.1. Theoretical engagement and coverage of acceptance dimensions

From the retrieved journal articles ($N = 33$), 30 studies applied an explicit theoretical approach, although five studies were classified as miscellaneous due to a more informal use of acceptance constructs [213, 262–264], for example, rooted in behavioural economic theory [265], or loss aversion or cognitive dissonance theory [266]. Among the remaining studies ($N = 24$), seven integrated a two-dimensional approach by drawing on more than one established theory [26, 48, 255, 257, 267–269].²¹ Consequently, the sample is composed mainly of

studies applying a single framework, indicating an underlying deficit in developing integrated acceptance theories within the ‘hydrogen futures’ literature [2, 256].

In total, 16 theories (including adapted and extended frameworks) are represented by the 24 studies, as shown in Fig. 4. The largest representation among the sample ($N = 19$; 54.3%) corresponds to eight theories rooted in a socio-psychological approach (i.e. TRA, TPB, and NAM). Three other categories account for the remainder, wherein studies applied the TSA and 5D-DHAF [26, 48, 256, 270–272], technology acceptance models such as TAM and UTAUT [112, 269, 273, 274], and the SETA [112, 221, 222, 267, 275, 276] with a relatively similar frequency ($N = 7$, $N = 4$, $N = 5$). Additionally, 21 of the reviewed studies visualised their approach through a theoretical, conceptual, or empirical model, or combination thereof, highlighting the potential scope for developing an integrated hydrogen acceptance model through pooling of results.

Regarding multi-dimensionality, Fig. 5 suggests researchers are most likely to engage with four dimensions of social acceptance ($N = 15$), while there is a growing trend towards engaging with all five dimensions ($N = 7$), as reflected in recent contributions from researcher groups in Australia [222], India [254, 269, 277], and the UK [271]. Notably, of the seven studies engaging with all five dimensions, only one study is traced to before 2020 [253]. As a result, one-third of studies ($N = 11$) are restricted to either three ($N = 6$) or just two acceptance dimensions ($N = 5$), highlighting an underlying lack of multi-dimensionality in several earlier contributions to the hydrogen acceptance literature. As a result of recent developments, this trend has been somewhat reversed but still

²¹ The study of Smith et al. [270] is excluded here on the grounds that the TSA is absorbed by the 5D-DHAF, on which the authors indirectly drew.

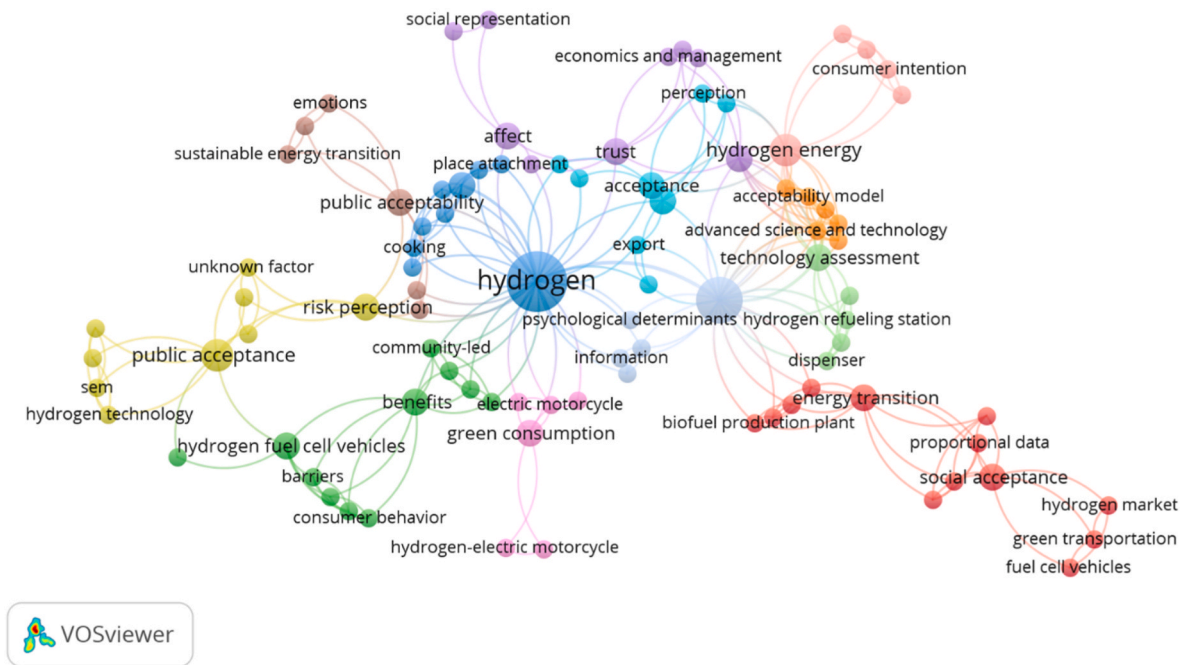


Fig. 3. Network visualisation of connected keywords in dataset (N = 33).

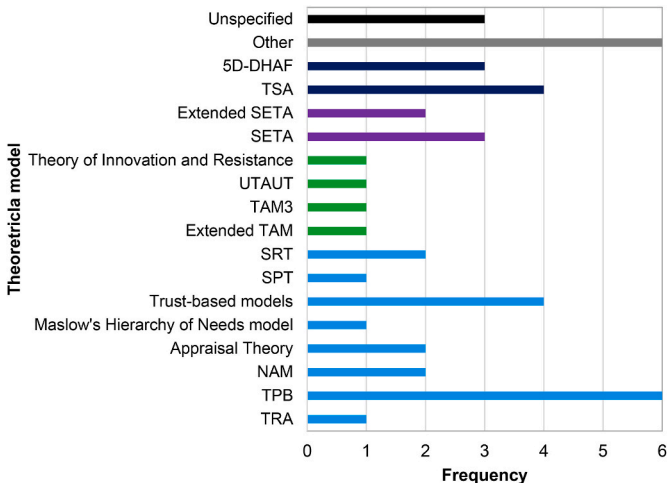


Fig. 4. Theoretical approaches applied in hydrogen energy acceptance studies (N = 33).

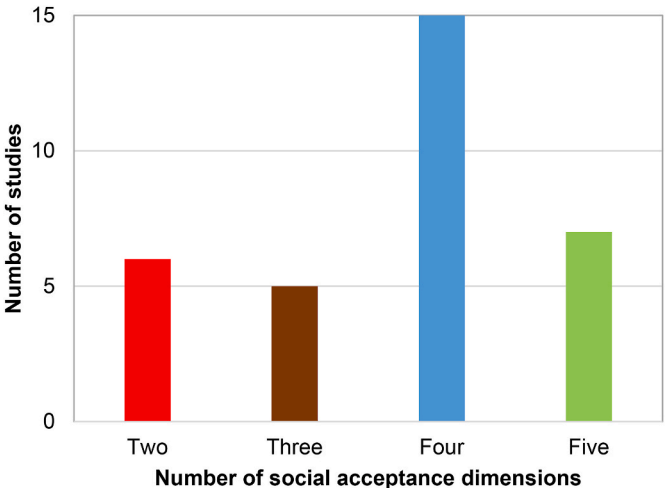


Fig. 5. Number of social acceptance dimensions engaged with across sample (N = 33).

falls short of studying at least four dimensions on average ($M = 3.7$). Fig. 6 substantiates the results by quantifying engagement levels with each dimension from across the hydrogen acceptance dataset. It emerges that all social acceptance studies have an explicit attitudinal dimension, given that the focus is on human perceptions. Although a logical finding, this observation has not been reported within studies to help benchmark other acceptance dimensions. Next, most studies entail a focus on socio-political acceptance ($N = 29$), which likely reflects the broader societal and energy policy implications of developing hydrogen-based energy systems and technologies [59,278]. Following the attitudinal and socio-political dimensions, the behavioural component of hydrogen acceptance is moderately represented across the sample ($N = 23$), as is the market dimension ($N = 21$). However, it emerges that neither dimension has proved integral to prior acceptance studies, which is most evident in terms of the community acceptance dimension ($N = 17$). This finding is significant to the domestic hydrogen transition, as community acceptance is critical to

facilitating the development of local trials and changes to infrastructure, while supporting wider approval for a national hydrogen economy (i.e. socio-political acceptance) [58]. For example, factors influencing community acceptance may include public perceptions of equity and fairness linked to spatial dynamics, alongside place attachment and place identity [28]. The partial representation of community acceptance may be somewhat technology-specific, given that 12 studies engaged with hydrogen transport applications (mainly HFCVs), of which only four included a focus on community acceptance. By contrast, six out of the eight studies focusing on HFSs engaged with community acceptance [221,253,257, 266,267,276]. Notably, all but one study on HFSs has Huijts as the lead author, reflecting a continuum in community acceptance scholarship following the formulation of the SETA model in 2012 [109]. Overall, the data suggests that around 30% of studies, on average, fall short of engaging with at least four dimensions of social acceptance, highlighting

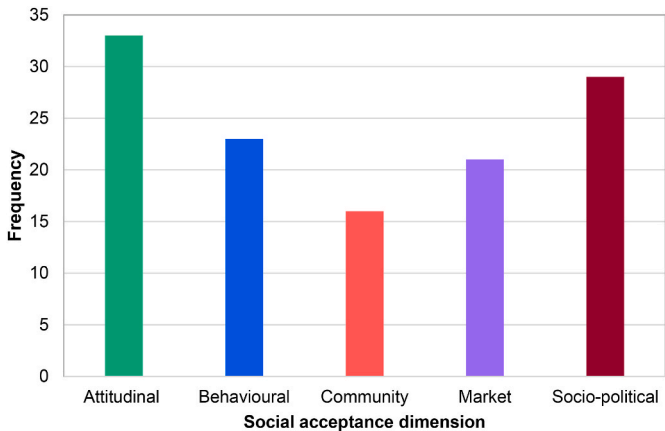


Fig. 6. Engagement with social acceptance dimensions (N = 33).

the need to move ‘beyond the triangle of renewable energy acceptance’ [58].

4.1.2. Integration of acceptance constructs in hydrogen energy studies

The analysis of hydrogen acceptance studies focuses on 13 constructs representing eight dimensions, as depicted in Fig. 7 (see Table S6): psychological (dark blue); financial perceptions (red); environmental perceptions (green); technological perceptions (orange); perceived effects (light blue); emotional response (purple); safety perceptions (brown); and social trust (gold).

From the original SETA model, the following constructs are represented directly: perceived risks, perceived costs, perceive benefits, positive emotions, negative emotions (i.e. ‘affect’) and social trust (i.e. ‘trust’). However, to delineate clearer boundaries between acceptance constructs, perceived effects are categorised within this study as comprehensive perceived risks, costs, and benefits (see Table 3), thereby differentiating more clearly between environmental, technological, financial, and safety perceptions. Additionally, the SETA included ‘experience’ which is translated into ‘awareness’ here, alongside ‘knowledge’ which is separated into ‘objective’ and ‘subjective’ knowledge.

As elaborated within the DHAM, constructs such as financial, environmental, technological, and safety perceptions are introduced from other theories, although some of these aspects appear less explicitly within the SETA, while other constructs are dropped due to their low frequency across the sample. Table 3 forecasts the final contribution of this study by defining each construct to the context of the domestic hydrogen transition. Accordingly, the holistic approach taken within this study internalises Scovell’s and Walton’s [115] observation to account for salient beliefs about water resources, infrastructure

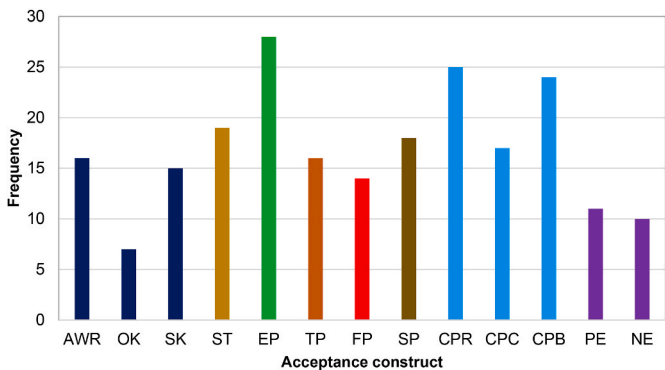


Fig. 7. Engagement in technology acceptance constructs across hydrogen energy studies (N = 33).

Table 3
Predictors of domestic hydrogen energy acceptance.

Acceptance predictor	Definition in the context of hydrogen energy acceptance
Awareness	<ul style="list-style-type: none">Level of familiarity with hydrogen fuel and hydrogen energy technologies, including narratives around the hydrogen energy transition
Objective knowledge	<ul style="list-style-type: none">Factual knowledge of hydrogen fuel regarding its properties, characteristics, applications, and history
Subjective Knowledge	<ul style="list-style-type: none">Self-rated knowledge of hydrogen fuel regarding its properties, characteristics, applications, and history
Social Trust	<ul style="list-style-type: none">Trust in the key actors and stakeholders responsible for supporting a cost-effective, efficient, and fair transition to hydrogen homes
Environmental Perceptions	<ul style="list-style-type: none">Perceived environmental benefits and risks associated with the domestic hydrogen transition and hydrogen homes appliances, as shaped by underlying attitudes towards climate change
Technological Perceptions	<ul style="list-style-type: none">Perceptions regarding the overall relative advantage of hydrogen home appliances compared to existing gas appliances, as shaped by underlying levels of technology engagement and experience
Financial perceptions	<ul style="list-style-type: none">Expectations regarding the potential purchasing, running, and maintenance costs of hydrogen home appliances
Safety Perceptions	<ul style="list-style-type: none">Perceived safety benefits and risks associated with the domestic hydrogen transition and hydrogen homes appliances
Comprehensive Perceived Risks	<ul style="list-style-type: none">Perceptions of potential (non-safety related) risks and disruptive impacts linked to the development and implementation of hydrogen infrastructure and technologies for domestic heating and cooking
Comprehensive Perceived Costs	<ul style="list-style-type: none">Perceptions of potential macro-economic, social, environmental, community, and individual costs linked to the development and implementation of hydrogen infrastructure and technologies for domestic heating and cooking
Comprehensive Perceived Benefits	<ul style="list-style-type: none">Perceptions of potential macro-economic, social, environmental, community, and individual benefits linked to the development and implementation of hydrogen infrastructure and technologies for domestic heating and cooking
Positive Emotions	<ul style="list-style-type: none">Feelings of satisfaction, calmness, confidence, optimism, and other positive emotions towards the domestic hydrogen transition and hydrogen homes appliances
Negative Emotions	<ul style="list-style-type: none">Feelings of discontent, worry, fear, pessimism, and other negative emotions associated with the domestic hydrogen transition and hydrogen homes appliances

Source: Authors’ compilation based on [82,87,109,253].

developments, job creation, and technology substitution when considering the hydrogen acceptance context.

Overall, most studies engage with the dimension of environmental perceptions (N = 28), followed by perceived effects, which is composed of benefits, costs, and risks (M = 22.0). Social trust ranked next (N = 19), followed by safety perceptions (N = 18), technological perceptions (N = 16), financial perceptions (N = 14), psychological aspects linked to awareness and knowledge (M = 12.7), and finally, positive and negative emotions (M = 10.5). Within constructs composed of multiple items, at least three critical patterns emerge which influence the overall results. Firstly, at the psychological level, objective knowledge (N = 7) is significantly underexamined in comparison to both awareness (N = 16) and subjective knowledge (N = 15), representing the less frequently engaged indicator across all measures.

Secondly, in terms of perceived effects, benefits (N = 24) and risks (N = 25) are examined with a high frequency, ranking behind environmental benefits, whereas perceived costs (N = 17) is relatively underexamined but still ranks ahead of seven other constructs. This result in is partial agreement with Scovell’s [82] conclusion that perceived costs has been less explored compared to benefits and risks, but also contradicts the verdict that perceived costs is more underexplored than several other acceptance constructs.

Lastly, the analysis suggests that researchers tend to include both

positive and negative emotions when examining the affective dimension of hydrogen acceptance, which is recommended to capture the paradoxical nature of technology perceptions [158]. While this dual focus may be anticipated, it is important to clarify whether either side of the emotional spectrum has received more focus in studies to date. Such a skewing, if detected across a larger sample size, would infer more interaction with perceived benefits in the case of a positive focus, whereas perceived risks and costs would feature under a negative lens. Accounting for a spectrum of emotional responses [279] is needed to reflect the paradoxical nature of technology adoption [158]; characterised by potential friction between different emotional states [280, 281] and ‘blends of emotions’ [63] in view of perceived risks, costs, and benefits.

AWR = Awareness; OK = Objective Knowledge; SK = Subjective Knowledge; ST = Social Trust; EP = Environmental Perceptions; TP = Technological Perceptions; FP = Financial Perceptions; SP = Safety Perceptions; CPR = Comprehensive Perceived Risks; CPC = Comprehensive Perceived Costs; CPB = Comprehensive Perceived Benefits; PE = Positive Emotions; NE = Negative Emotions.

4.2. Domestic energy technology acceptance

The systematic literature review on domestic energy acceptance, as supported by snowball sampling ($N = 42$), accounted for 25,854 respondents ($M = 615.6$; $SD = 645.5$) from across 27 countries, with 70% of the representation originating from Asia and Europe.²² To explore the patterns within this dataset, the VOSviewer bibliometric software tool [261] was employed for network visualisation purposes.

Mapping the relationships between 95 connected keywords ($N = 163$) led to the formation of ten clusters, revolving around keywords such as social acceptance, technology acceptance and TAM, diffusion of microgeneration technologies, perceived benefits and psychological benefits, and SEM (see Fig. 8). Different dimensions of acceptance were also captured within the visualisation, including the socio-political dimension (e.g. business ethics and sustainability), market dimension (e.g. willingness-to-pay, affordability, and purchase intention), attitudinal dimension (product knowledge and knowledge transmission), and behavioural dimension (e.g. intention-behaviour gap). However, clusters representing the community acceptance dimensions were less visible.

4.2.1. Theoretical engagement and coverage of acceptance dimensions

From the retrieved journal articles ($N = 42$), 12 studies integrated at least two theoretical frameworks into their conceptual approach [81, 144, 212, 282–290], whereas 30 employed a single framework. Among the 12 studies adopting a hybrid approach, 9 focused on rooftop solar PV, suggesting a stronger propensity for integration among solar acceptance scholars. Notably, three studies [81, 212, 284] within this group²³ also incorporated more than two theoretical frameworks, thereby aligning to the underlying premise of this contribution.

The most frequently applied theoretical approach ($N = 20$) stems from the socio-psychological school of thought rooted in the TRA and TPB, with extended versions of the TPB dominating this group ($N = 12$). Rogers' DoI theory also features prominently ($N = 12$), with most scholars extending the framework in their analyses ($N = 10$). Notably, extended versions of the SETA ($N = 12$) are represented with the same frequency as extended TBP and DoI approaches, confirming the critical uptake of the framework within the last decade (see Fig. 9). Next,

²² Asia = 10; Europe = 9; Middle East = 3; North America = 2; Africa = 1; Central America = 1; Oceania = 1. Less critical focus is placed on examining the domestic energy technology dataset as the primary focus of this study is on hydrogen acceptance.

²³ Two studies on rooftop solar PV and one on domestic microgeneration technologies.

various applications of the TAM and its derivatives such the UTAUT account for most of the remaining studies ($N = 11$) while a selection of frameworks including the TSA are represented by a single study ($N = 5$).²⁴ Consequently, most studies within the dataset have strived to adapt or extend seminal frameworks when examining domestic energy acceptance, thereby advancing theoretical engagement to an extent.

Evidence suggests a growing trend regarding the integration of theoretical or conceptual models, as visualised within journal papers. Across the dataset, nearly 80% of studies ($N = 33$) supported their conceptual approach or proposed hypotheses with a corresponding figure, with all studies after 2020 ($N = 18$) reflecting this decision. Among the studies lacking a visualisation, the first four studies in the dataset (1993–2013) accounted for this group, alongside five studies in the intervening years (2014–2019). Based on these trends, it may be inferred that the incorporation of a supporting visual has become a research norm for studies grounded in theory.

In terms of multi-dimensionality, Fig. 10 shows that researchers tend to engage with four dimensions of social acceptance ($N = 24$), although a minority of studies focused on just two dimensions ($N = 4$). Meanwhile, the remaining studies were split equally between three and five dimensions ($N = 7$). The results suggest a multi-dimensional approach to the study of domestic energy acceptance is somewhat established among the research community ($M = 3.8$). Nevertheless, few scholars have explicitly engaged with all social acceptance aspects proposed with the 5D-DHAF.

Fig. 11 provides an explanation for these trends by quantifying engagement levels with each dimension from across the dataset. In contrast to the attitudinal dimension, the behavioural component of social acceptance is not a prerequisite for analysis ($N = 39$), while the market acceptance dimension is slightly less represented ($N = 35$), as are socio-political aspects ($N = 33$). Taken together, these findings imply that around 15% of studies, on average, overlook either behavioural, financial, or broader societal implications of technology change. However, community acceptance ($N = 12$) is the most overlooked dimension within the literature on domestic energy technologies.

Mirroring the logic that attitudinal acceptance is a prerequisite dimension, while behavioural acceptance is typically incorporated into hypotheses, with market and socio-political aspects relatively well-represented, it follows that community-level perceptions may prove less pertinent to domestic energy adoption. However, close to 30% of studies within the dataset challenge this notion by incorporating a direct focus on how adopting a given household technology may interact with community acceptance.

Considering the perceptions of both adopters and non-adopters, focal points may range from impacts to the local area and property, to behavioural feedback loops between neighbours and local residents [291], which could imply different social pressures and market dynamics (i.e. changes to land and property value). Accordingly, acceptance at the community level interacts strongly with other areas, reinforcing the utility of incorporating factors from across all five acceptance dimensions.

4.2.2. Integration of acceptance constructs in domestic energy studies

The analysis of acceptance constructs across the sample (see Table S7) shows most engagement with the environmental dimension ($N = 35$), followed closely by technological perceptions ($N = 33$), and financial perceptions ($N = 31$). Thereafter, perceived effects is the most represented dimension ($M = 24$), while the remaining areas are significantly underexplored. Foremost, safety perceptions are rarely accounted for in domestic energy acceptance studies ($N = 4$), while the

²⁴ Within this group, we include the study of Xu et al. [403], which drew on the Value-Based Adoption Model (VAM) proposed by Kim et al. [404]. The VAM examines the effects of perceived benefits and sacrifices on perceived value, which predicts adoption intention.

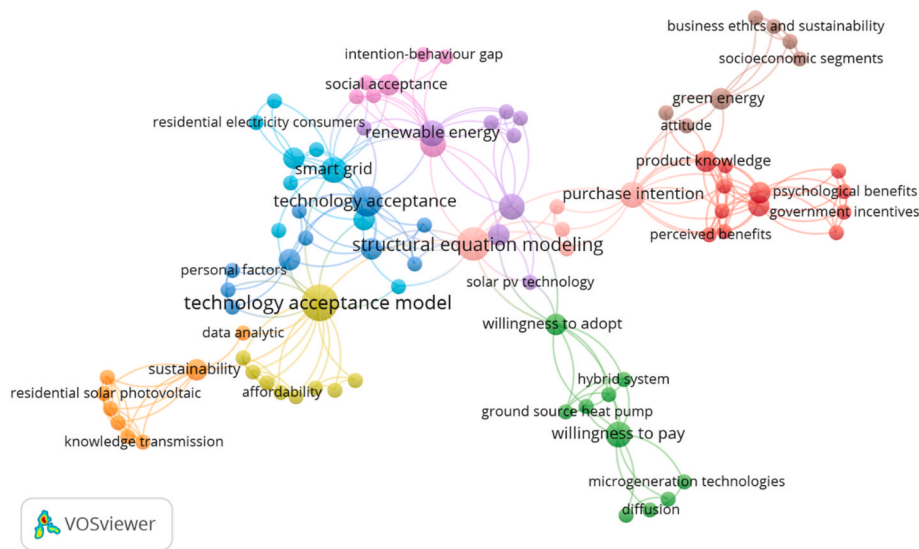


Fig. 8. Network visualisation of connected keywords in dataset (N = 42).

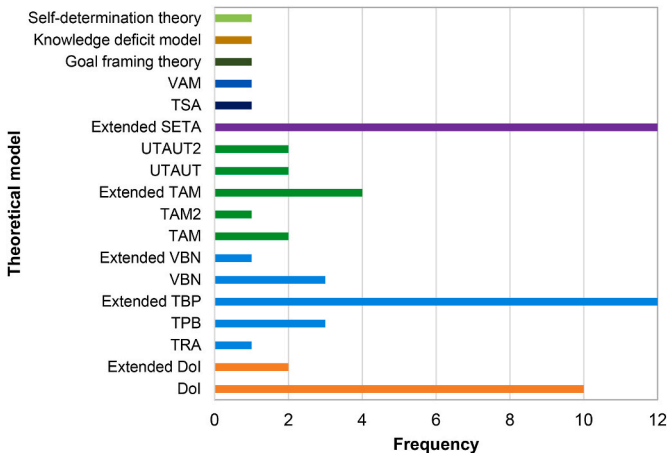


Fig. 9. Theoretical approaches applied in domestic energy acceptance studies (N = 42).

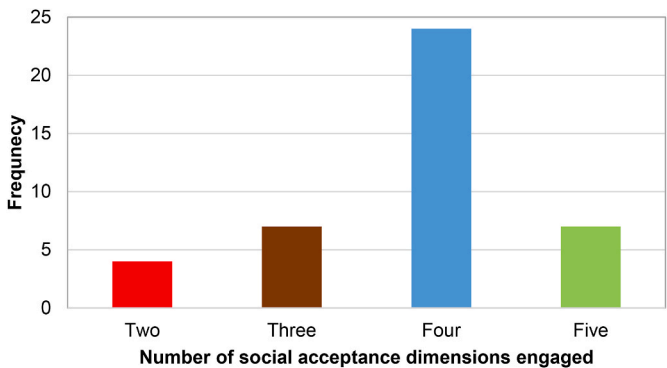


Fig. 10. Number of social acceptance dimensions engaged with across sample (N = 42).

emotional dimension is commonly overlooked ($M = 7.5$). Finally, psychological constructs ($M = 13.7$) and social trust ($N = 13$) have a near equal weighting across the sample, which fall towards the lower end of engagement.

The findings of this review both align with and contradict results

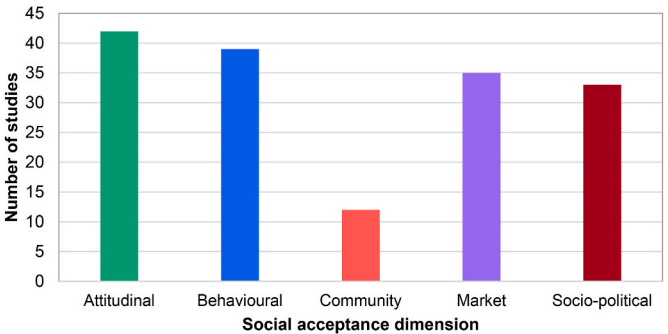


Fig. 11. Engagement with social acceptance dimensions (N = 42).

reported by Marikyan et al. [292] covering the period 2002 to 2017 ($N = 143$),²⁵ whereby 101 articles were retrieved through snowballing. The authors noted that environmental and financial factors (i.e. benefits) were less frequently discussed across the sample, while least attention was given to socio-cognitive and emotional factors [292]. By contrast, Fig. 12 suggests environmental and financial perceptions are well represented, whereas in agreement with [292], knowledge, social trust, and emotional response are poorly represented. Additionally, Fig. 12 supports the strong representation of technological perceptions and perceived benefits, as also reported for the period 2002–2017 [292].

Given the different time periods and research angles, it is somewhat anticipated that trends may have evolved within the last five years; or reflect different approaches wherein theoretical foundations are applied more strictly. Most critically, following the premise of this study, Marikyan and colleagues [292] called for a multi-dimensional approach, suggesting “future research could examine the emotional, psychological, symbolic, functional and financial antecedents that trigger users to accept or reject smart home products.”

Similarly, Ozaki [293] argues that consumer acceptance of ‘green’ electricity hinges on a combination of external factors such as costs and performance, as well as socio-psychological factors such as identity, values, beliefs, and cultural disposition [293]. Additionally, reducing carbon dioxide emissions, saving money on energy bills, and demonstrating environmental commitment and innovativeness have been

²⁵ The most represented year in the review period was 2016 ($N = 21$), compared to a mean of 9 articles for the search period.

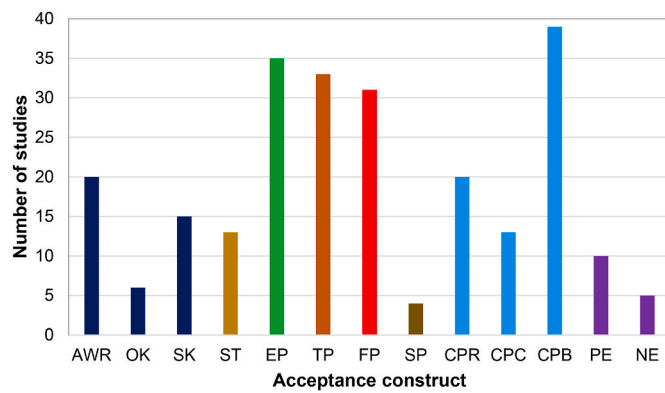


Fig. 12. Engagement in technology acceptance constructs across domestic energy studies (N = 42).

AWR = Awareness; OK = Objective Knowledge; SK = Subjective Knowledge; ST = Social Trust; EP = Environmental Perceptions; TP = Technological Perceptions; FP = Financial Perceptions; SP = Safety Perceptions; CPR = Comprehensive Perceived Risks; CPC = Comprehensive Perceived Costs; CPB = Comprehensive Perceived Benefits; PE = Positive Emotions; NE = Negative Emotions.

identified as drivers of household adoption for microgeneration heat technologies in the UK context [294,295], whereas barriers include financial concerns, and uncertainties over performance and reliability.

4.3. Comparative analysis of energy acceptance literatures

4.3.1. Insights from bibliometric analysis

Following the structured analysis of acceptance for hydrogen and domestic energy technologies, the two datasets were merged in VOS-viewer, with the aim of validating previous observations and detecting critical relationships. A total of 268 keywords were processed from the final dataset (N = 75), resulting in 45 connected keywords with the minimum number of occurrences set to two. Following the structure of this analysis, Fig. 13 provides a network visualisation to support the summary analysis, while Fig. 14 presents a density visualisation, wherein keywords are clearly highlighted for improved readability of results.

In total, eight clusters were formed ranging from five to seven items. Notably, various representations of ‘acceptance’ emerge from the visualisation, including ‘consumer acceptance’ and ‘public acceptability’ (Cluster 1, red), ‘social acceptance’ (Cluster 2, green), ‘public acceptance’ (Cluster 3, dark blue), ‘technology acceptance’ (Cluster 4, yellow; Cluster 5, purple), and ‘willingness to adopt’ (Cluster 8, brown). This observation reflects scholarly debate regarding the fuzziness of acceptance terminologies within the literature [296,297], which has led to calls for clearer demarcation [58,227,298].

The affective dimension of technology acceptance is represented by ‘emotions’ and ‘affect’ (Cluster 1; Cluster 7, orange), reinforcing the relevance of this often overlooked construct. Additionally, Cluster 6 (light blue) includes ‘environmental concern’, which registers directly to the environmental perceptions construct, with an explicit emotional connotation. Cluster 3 captures ‘consumer behaviour’ while Cluster 5 includes ‘consumer attitude’, thereby highlighting the behavioural and attitudinal acceptance dimensions, which are also represented elsewhere via ‘ecological lifestyle’ and ‘product knowledge’ (Cluster 6), with Cluster 7 including an additional behavioural component via ‘social practices’. Critically, risk perceptions and perceived benefits feature in Clusters 1 and 3, validating the relevance of the perceived effects construct.

The socio-political level is reflected by ‘energy policy’ (Cluster 4), while market acceptance is denoted in terms of ‘purchase intention’ (Cluster 6) and ‘willingness to pay’ (Cluster 8). However, consistent with

patterns observed in Figs. 3 and 8, the community acceptance dimension remains obscured when mapping the relationship between keywords. In addition to displaying specific technologies from both contexts across various clusters, the visualisation entails a specific theoretical component in Cluster 8 vis-à-vis the Theory of Planned Behaviour, which is connected to ‘structural equation modelling’ (SEM) and ‘consumers’, alongside ‘willingness to pay’ and ‘willingness to adopt’.

As an extension of traditional linear regression modelling techniques, otherwise referred to as the ‘second generation’ of multivariate analysis [299], SEM provides a flexible technique [300] for explaining “multiple statistical relationships simultaneously through visualisation and model validation” [301]. Consequently, SEM has been widely adopted by researchers across the social sciences [302–305], with notable proliferation among energy acceptance scholars in recent years [71,246,306–308].

SEM featured in approximately 45% of the reviewed studies (N = 34), with a somewhat stronger representation within domestic energy acceptance studies (N = 21, ~47%) compared to hydrogen acceptance studies (N = 13, ~39%). For the most part, the remaining studies employed a range of regression analysis techniques [309]. The implications of employing respective SEM techniques (CB-SEM and PLS-SEM) are further explored in Supplementary Note 6 (see Fig. S5), reflecting the need for a deeper exploratory focus on advancing theories of domestic hydrogen acceptance.

4.3.2. Insights from theoretical engagement and coverage of acceptance dimensions

In view of theoretical approaches, hydrogen acceptance studies present somewhat divergent trends compared to the literature on domestic energy acceptance. Foremost, DoI theory is absent from the hydrogen dataset, although associated constructs may be subsumed within TAM and other models at times. Nevertheless, this finding is significant in demonstrating a deficiency in considering critical acceptance factors linked to perceived technology attributes, such as relative advantage and compatibility. Accordingly, it would follow that the market acceptance dimension is more overlooked within the hydrogen acceptance literature, which is corroborated by Fig. 15.

The combined prominence of the TAM and SETA model within the domestic energy acceptance literature (38.3%), compared to the hydrogen acceptance dataset (25.8%), may explain the disparity between engagement with behavioural acceptance (see Fig. 15). By contrast, socio-psychological theories feature much more prominently in the hydrogen acceptance literature (54.3%) compared to the domestic energy dataset (33.3%). Consequently, there is less diversity regarding theoretical application across hydrogen studies, although the more recent uptake of the TSA and 5D-DHAF partially offset this imbalance. Overall, these trends support the critical need for a more unified approach to the study of hydrogen acceptance, especially in the context of domestic energy technologies, which can be achieved by developing an integrated framework.

Hydrogen studies also had less variance in terms of engagement across available acceptance dimensions ($SD = 4.0$) compared to domestic energy studies ($SD = 9.0$). This trend is reflected by the hydrogen group having a comparatively lower representation across four dimensions (~46.9%) compared to the domestic energy group (~57.1%). Furthermore, the hydrogen sample was characterised by both weaker and stronger levels of engagement with the 5D-DHAF, following a higher frequency for engaging with two dimensions (~18.8%) and five dimensions (~21.9%) compared to domestic energy studies (~9.5% and 16.7%). However, the two datasets proved comparable when considering engagement across three acceptance dimensions (Hydrogen energy = ~15.6%; Domestic energy = ~16.7%).

It may be concluded that hydrogen researchers are more likely to maximise engagement across the 5D-DHAF, whereas domestic energy researchers have a slightly stronger tendency to interact with at least four dimensions (73.8% compared to 68.8%). Encouragingly, the

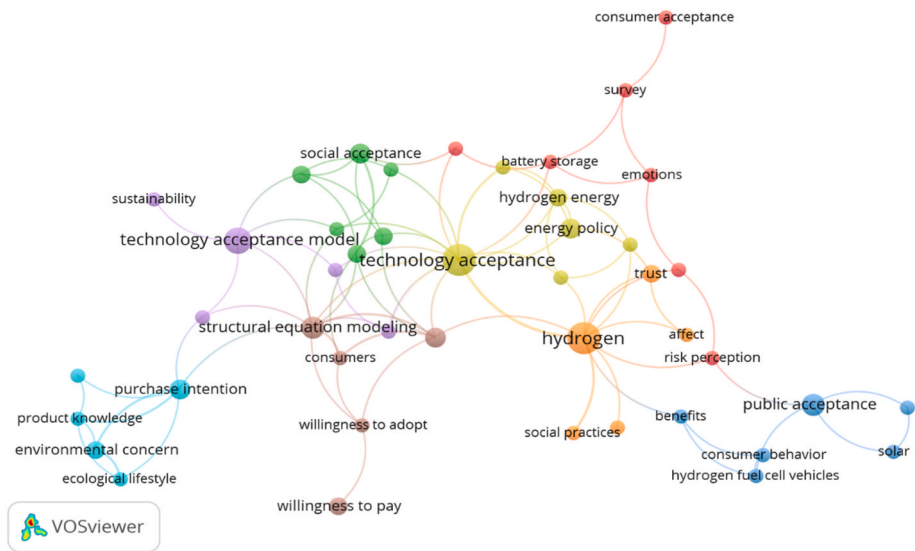


Fig. 13. Network visualisation of connected keywords in dataset (N = 75).

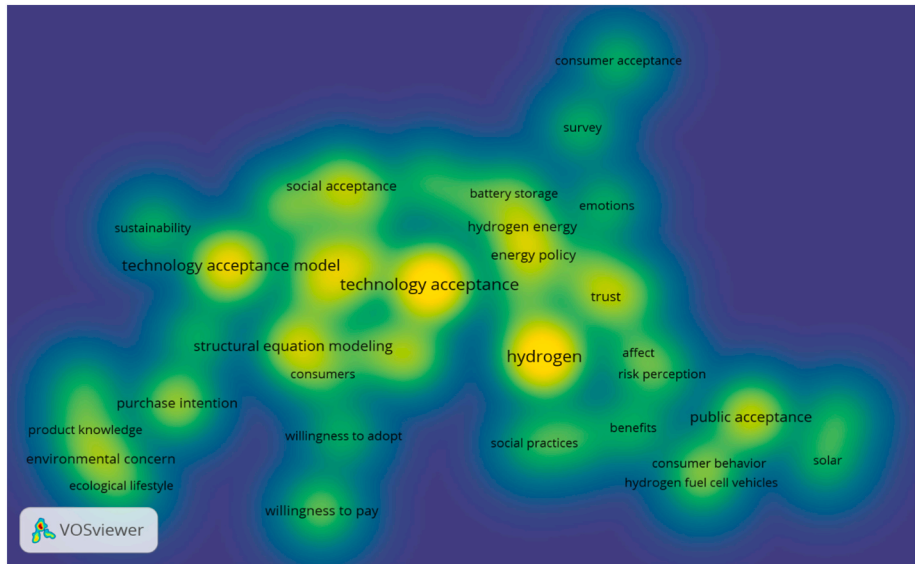


Fig. 14. Density visualisation of connected keywords in dataset (N = 75).

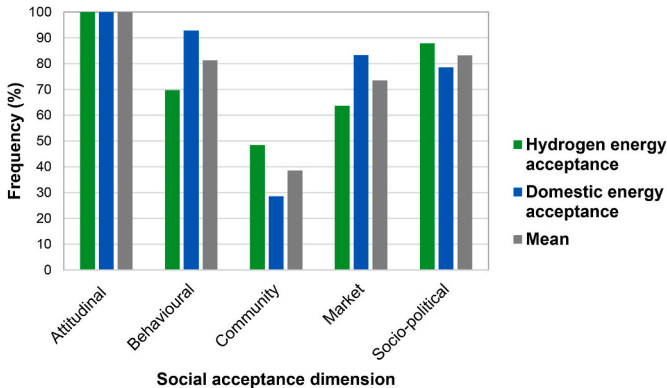


Fig. 15. Comparative analysis of engagement in social acceptance dimensions across sample (N = 75).

combined sample shows advancement towards engaging with a more multi-dimensional approach to energy acceptance than envisioned within the TSA. Nevertheless, significant scope exists for consolidating research efforts towards capturing a fuller representation of technology or social acceptance, as conceptualised within the 5D-DHAF.

The lack of engagement across the 5D-DHAF can be traced to four dimensions, whereas attitudinal acceptance is a prerequisite of understanding consumer response to energy technologies. Across the sample, socio-political ($M = 83.2$) and behavioural acceptance ($M = 81.3$) are represented most frequently behind attitudinal acceptance. However, as highlighted, hydrogen energy acceptance studies are more likely to integrate a socio-political lens ($M = 87.9$), while domestic energy acceptance studies usually include a behavioural focus ($M = 92.9$), which is significantly less common among hydrogen researchers ($M = 69.7$). The market acceptance dimension ranks next ($M = 73.5$) with higher representation among domestic energy studies ($M = 83.3$), while community acceptance is the most underexplored dimension ($M = 38.5$).

To an extent, hydrogen acceptance researchers may leverage lessons

from domestic energy studies when seeking to elevate engagement in behavioural and market acceptance dimensions. Conversely, domestic energy acceptance scholars may learn from their hydrogen counterparts when striving to engage more actively with community-level factors. Nevertheless, both research strands are yet to consistently explore community acceptance factors, which emerges as an outlier within this analysis. Through the process of an integrated, comparative review grounded in systematic methods, research deficits at the theoretical level have been expounded through a novel approach, which can be elaborated on or otherwise replicated in future studies.

4.3.3. Insights from integration of acceptance constructs

Several key insights can be extracted from comparing the use of acceptance constructs across the respective datasets, as presented in Fig. 16. Both research strands present comparable engagement with the environmental perceptions (ENV: $M = 84.1$) and awareness constructs (AWR: $M = 48.1$). Notably, environmental perceptions ranks first across the sample, whereas awareness ranks sixth, albeit ahead of both subjective knowledge (SK: $M = 40.6$) and objective knowledge (OK: $M = 17.7$), which rank ninth and last (13th) respectively. Consequently, knowledge-related aspects are significantly underexplored compared to awareness, although subjective knowledge is more commonly examined within hydrogen studies ($M = 45.5$).

Fig. 16 shows that hydrogen studies present a higher comparative representation across most acceptance constructs, with three notable exceptions: technological perceptions (−21.3 for hydrogen studies); financial perceptions (−22.2 for hydrogen studies); and comprehensive perceived benefits (−14.2 for hydrogen studies). The identified factors rank second (CPB: $M = 82.8$), third (TP: $M = 63.5$), and fifth (FP: $M = 58.1$) across the sample, reinforcing critical opportunities to support the “social science research agenda for hydrogen transitions” [26]. As a result, insights from domestic energy acceptance studies can be directly leveraged to advance hydrogen research in the context of home heating and cooking appliances, through a stronger focus on perceived benefits, alongside technology and financial perceptions. Nevertheless, hydrogen acceptance researchers tend to engage more with perceived risks, and less with perceived costs, as compared to perceived benefits, therefore, a stronger balance of representation is needed across associated measures of perceived effects.

While the highlighted constructs warrant increased attention in view

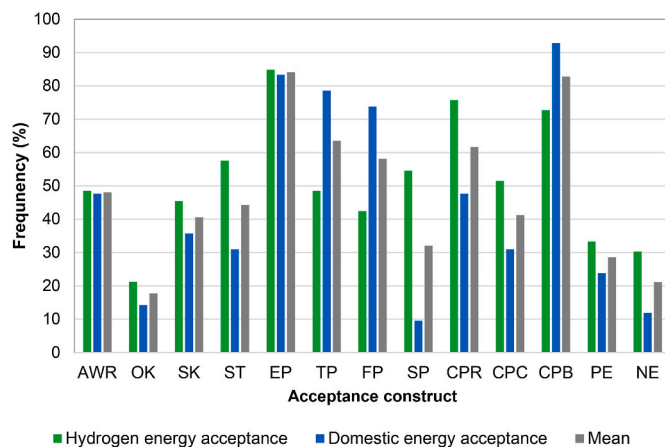


Fig. 16. Comparative analysis of engagement in technology acceptance constructs across sample ($N = 75$).

AWR = Awareness; OK = Objective Knowledge; SK = Subjective Knowledge; ST = Social Trust; EP = Environmental Perceptions; TP = Technological Perceptions; FP = Financial Perceptions; SP = Safety Perceptions; CPR = Comprehensive Perceived Risks; CPC = Comprehensive Perceived Costs; CPB = Comprehensive Perceived Benefits; PE = Positive Emotions; NE = Negative Emotions.

of their prevalence within domestic energy studies, the overall results stress the need to increase research engagement across multiple acceptance dimensions. Foremost, more extensive insights are needed regarding socio-psychological variables such as knowledge, awareness, and trust, in addition to emotional factors. Furthermore, the emotional spectrum should be explored in relation to specific drivers such as risk perceptions.

Corroborating these observations, Fig. 17 emphasises a predominantly slow uptake regarding efforts to operationalise multiple acceptance constructs within studies. While the sample ($N = 58$) is restricted to seven years,²⁶ there is no strong evidence of overall growth, although hydrogen acceptance studies have performed significantly better within the last two recorded years (see Table S8). As a broad guideline, it is recommended that acceptance studies engage with at least 8 of the 13 constructs measured in this review, which has only occurred within a single year for one technology (hydrogen acceptance studies in 2022: $M = 8.8$). While an outlier in this study, this metric reflects the direction in which energy acceptance research should rapidly move for deriving more comprehensive and critical insights on consumer perspectives. The final section synthesises the presented evidence by constructing a new model, which can be adapted and extended in future work to consolidate a Unified Theory of Domestic Hydrogen Acceptance.

5. The Domestic Hydrogen Acceptance Model

5.1. Theoretical foundations of the DHAM

Through a novel operationalisation of traditional and emergent technology acceptance constructs, the DHAM synthesises a range of critical theories to support the goal of increasing predictive power in research models. The proposed framework reflects the importance of linking established acceptance constructs such as knowledge and awareness [147] to emotional response, as specified by Kulviwat et al. [89] in the CAT model. Specifically, the CAT model argues that a multi-dimensional focus is essential to reflect scenarios in which technology adoption is a choice, as opposed to being mandated, wherein consumers arrive to their decisions through both cognitive and emotional processes [89].

Similarly, the DHAM incorporates the fundamentals of DoI [147] by directly modelling technological perceptions, reflecting the importance of this construct in the context of domestic energy acceptance [79]. In conjunction, the DHAM can be characterised as an expectancy-value model [175] in relation to capturing performance expectations for hydrogen boilers and hobs, thereby resonating with the TPB.

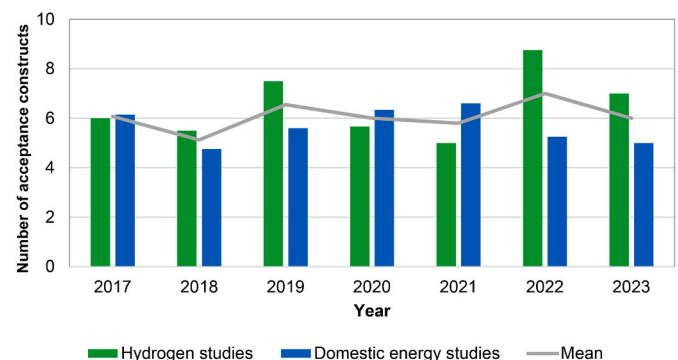


Fig. 17. Engagement with acceptance constructs, 2017–2023.

²⁶ 2017 is taken as a start year, since 2017 and 2018 are first consecutive years in which at least two studies for each dataset were retrieved for the SLR.

Additionally, consumer expectations across environmental, financial, and safety dimensions are incorporated into the framework.

Notably, by including environmental perceptions as an exogenous construct, the DHAM internalises elements of Stern's VBN theory [310] such as normative beliefs about climate change [188]. Such beliefs have been shown to evoke emotional responses to sustainable energy innovations [311] such as heat pumps [312]. The framework also leverages from UTAUT2 [200] by incorporating financial perceptions as an antecedent of comprehensive perceived effects (i.e. risks, costs, and benefits).

Fundamentally, the DHAM presents a combined, integrated model, thereby following in the tradition of Taylor and Todd as captured in the Combined TAM and TPB (C-TAM-TPB) [181], and associated multi-dimensional approaches to modelling technology acceptance [174,211,226,313]. Through this focus, the potential diffusion of domestic hydrogen technologies is influenced by dynamic interactions between acceptance constructs [58,82], in conjunction with other critical drivers such as political and techno-economic factors [6,59]. Notably, Frankhauser et al. [314] recently highlighted the need to navigate between “political, economic, legal and behavioural” dimensions to support net-zero ambitions, which is reflected via the focus on consumer behaviour within the DHAM.

While the 5D-DHAF specifies that cognitive legitimacy is a prerequisite for facilitating behavioural acceptance, as realised through the adoption of hydrogen home appliances; the DHAM extends the framework by integrating emotional valence [267,315] into the equation of prospective technology acceptance. Through this lens, the proposed conceptual framework is cognisant of the potential effects of emotions on technology acceptance and adoption [316], taking stock of prior efforts to develop an ‘emotional-TAM’ in other contexts [317]. Notably, appraisal theory posits that specific emotions arise because of one's cognitive and affective appraisal of a situation [318]. As a novel contribution, the DHAM explicitly reflects the premise that energy acceptance and subsequent adoption are shaped via an interplay between rational thought and emotional response [81,242], as depicted in Fig. 18.

5.2. Hypothesised relationships within the DHAM

The proposed model consists of 13 constructs, which are hypothesised to predict domestic hydrogen acceptance, in turn predicting domestic hydrogen adoption potential (see Table 4). As a result, the DHAM operationalises a similar number of constructs compared to the SETA model, albeit with various adaptations to improve model parsimony to the technology-specific context of hydrogen homes.

Within the DHAM, five exogenous constructs are formulated: (hydrogen) Awareness (AWR); Social Trust (ST); Environmental Perceptions (EP); Technological Perceptions (TP); and Financial Perceptions (FP). Objective Knowledge (OK) and Subjective Knowledge (SK) are hypothesised to mediate the relationship between AWR and SP.

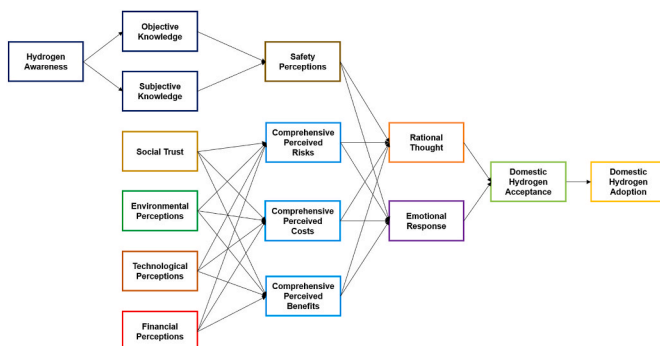


Fig. 18. The domestic hydrogen acceptance model.

Therefore, AWR has direct effects on both types of knowledge. The remaining exogenous constructs have direct effects on Comprehensive Perceived Effects (CPE), composed of perceived risks (CPR), costs (CPC), and benefits (CPB).

In summary, when ST is weaker, and EP, TP, and FP are negative, consumers are more likely to perceive higher risks and costs associated with the domestic hydrogen transition and the introduction of hydrogen home appliances. Conversely, CPB will stem from positive environmental, technological, and financial perceptions, alongside stronger levels of social trust. Critically, a distinction is drawn between FP, which entails expectations regarding purchasing and running costs for hydrogen homes, and CPC, which relates to broader economic, as well as social and environmental costs.

Similarly, within the DHAM, safety perceptions and perceived risks are modelled separately, in view of the anticipated importance of safety factors to household decision-making. For example, Scott and Powells [26,27] identified safety perceptions as an important aspect of domestic hydrogen acceptance, which has been validated in follow-up studies in the UK context [272,319]. Notably, national survey results from Australia found safety to be the most important factor in determining consumer willingness to use domestic hydrogen, while reliability of energy supply ranked second [320].²⁷ Consequently, in contrast to safety perceptions, perceived risks are characterised primarily in terms of concerns over disruptive impacts. Perceived disruptive impacts may extend from the street-level to the community-level, thereby entailing potential socio-economic and health risks to both households and local communities [28].

While there is a natural interplay between perceived risks and costs, the former is more strongly linked to anticipated issues associated with infrastructure development, while the latter corresponds to more tangible impacts which may be quantified, such as potential job or income loss. For example, in reference to perceived costs, Scovell and Walton [115] discuss the potential impacts of hydrogen technologies on energy security and supply, and market implications linked to competition with renewable energy technologies.

In turn, CPR, CPC, and CPB influence both cognitive attitudes and affective evaluations, as reflected by Rational Thought (RT) and

Table 4

Proposed hypotheses within the Domestic Hydrogen Acceptance Model.

Hypotheses	Relationship between acceptance constructs
H1a, H1b	Awareness (AWR) → Knowledge (OK; SK)
H2a, H2b	Knowledge (OK; SK) → Safety Perceptions (SP)
H3a–H3c	Social Trust (ST) → Comprehensive Perceived Effects (CPR, CPC, CPB)
H4a–H4c	Environmental Perceptions (EP) → Comprehensive Perceived Effects (CPR, CPC, CPB)
H5a–H5c	Technological Perceptions (TP) → Comprehensive Perceived Effects (CPR, CPC, CPB)
H6a–H6c	Financial Perceptions (FP) → Comprehensive Perceived Effects (CPR, CPC, CPB)
H7a, H7b	Safety Perceptions (SP) → Emotional Response (PE; NE)
H8	Safety Perceptions (SP) → Rational Thought (RT)
H8a–H8f	Comprehensive Perceived Effects (CPR, CPC, CPB) → Emotional Response (PE; NE)
H9a–H9c	Comprehensive Perceived Effects (CPR, CPC, CPB) → Rational Thought (RT)
H9a, H9b	Emotional Response (PE; NE) → Domestic Hydrogen Acceptance (DH-ACPT)
H10	Rational Thought (RT) → Domestic Hydrogen Acceptance (DH-ACPT)
H11	Domestic Hydrogen Acceptance (DH-ACPT) → Domestic Hydrogen Adoption (DH-ADPT)

²⁷ See Table 16 in Martin et al. [320] for a comparison of results from 2018 to 2021 wherein safety ranked first in both cases ahead of factors such as reliability of energy supply, fuel costs, the cost to modify appliances, and moreover, elimination of greenhouse gas emissions.

Emotional Response (ER) within the model, whereby ER is derived in relation to measures of Positive Emotions (PE) and Negative Emotions (NE). Together, RT and ER influence Domestic Hydrogen Acceptance (DH-ACPT), which predicts the potential for Domestic Hydrogen Adoption (DH-ADPT). Similarly, SP predicts DH-ACPT, as mediated by RT and ER. Accordingly, within the DHAM, acceptance provides a proxy for intention to adopt hydrogen appliances, wherein attitudinal acceptance is shaped by rational thought and emotional response, thereby merging the cognitive and affective dimensions of human decision-making.

5.2.1. Knowledge, awareness, and safety perceptions

The DHAM hypothesises that awareness of hydrogen increases both objective and subjective hydrogen knowledge, which in turn influence safety perceptions. Prior studies suggest the combined effect of higher awareness and knowledge is associated with more positive hydrogen safety perceptions [321], which increases the likelihood of consumer acceptance [322]. However, with higher objective knowledge, safety concerns may also become elevated in view of hydrogen's psychical and chemical properties [305].

Critically, safety challenges will be elevated in the context of residential hydrogen [59] as opposed to industrial use [18]. Hydrogen's distinct physical and chemical properties may give rise to negative safety perceptions [27], which could translate into feelings of fear and anxiety [323]. In various contexts, the explosive risks of hydrogen have been consistently highlighted by survey respondents [275,324–326], whereas safety benefits are less frequently cited [323], although neutral perceptions may also prevail [26]. Notably, consumers perceive greater safety risks regarding hydrogen cooking compared to hydrogen heating [27,272].²⁸ Evidence further suggests a more positive safety perception of induction hobs compared to gas cookers and prospective hydrogen hobs [272]. Additionally, fears may stem from risks associated with the underground storage of hydrogen [327,328].

For much of society, domestic hydrogen may evoke a range of positive or negative emotions linked to safety perceptions. On the one hand, the public may expect the new technology to have undergone stringent safety checks if approved for deployment [47,329]. Such perceptions could potentially ease safety concerns and instil a sense of consumer confidence [26,47,329]. Furthermore, in countries such as the UK, hydrogen may be perceived positively for eliminating the risk of carbon monoxide poisoning within the home [330]; especially among households experiencing fuel poverty where the risk is disproportionately higher [330]. However, general or specific concerns regarding the flammability of hydrogen [331], alongside other hazardous risk factors [332–334], could instead evoke feelings of fear and anxiety among consumers [27,323].

The DHAM hypothesises that dependent on the given consumer profile and situational context (e.g. family household vs single household), the causal chain between awareness and knowledge levels, safety perceptions, and emotional response is likely to be activated. Thus, a positive or negative association to safety may be observed according to the sample in question, wherein the technical knowledge level of lay respondents is likely to shape the observed relationship. As noted by Beasy et al. [335], technical knowledge may counteract negative safety perceptions. Critically, as technical knowledge increases, there is stronger likelihood that consumer attitudes will stem primarily from cognitive evaluations, as opposed to affective response.

5.2.2. Social trust and comprehensive perceived effects

Social trust is a complex, multi-dimensional construct [336], which can be explored in terms of both cognitive and emotional dimensions

[154,337], alongside specific areas such as institutional trust [338,339]. At the cognitive level, a further distinction can be made between 'competence-based' and 'integrated-based' trust [154,340]. Notably, in the Australian context, support for developing a national hydrogen economy was associated with social trust in the commitment and ability of government and industry towards tackling decarbonisation [222]. In the German context, Häußermann et al. [48] concluded that "acceptance of green hydrogen relies on trust in science, government, the media, and institutions that uphold distributive justice."

Regarding emerging energy technologies such as hydrogen, a deficit in social trust may elevate perceptions of risks and costs; whether at the macro-level, community-level, or household-level, thereby undermining the potential for social acceptance and subsequent adoption [271]. Accordingly, social trust is critical to ensuring that perceptions of potential benefits outweigh the combined negative effect of perceived risks and costs, which may prove challenging during the formative stage of technology diffusion when uncertainties accrue [341].

5.2.3. Environmental perceptions and comprehensive perceived effects

Attitude towards climate change, green consumption and related environmental aspects are anticipated to shape perceived effects of hydrogen technologies [254,255]. Foreseeably, if the low-carbon credentials of domestic hydrogen are supported, especially among consumers considering themselves to be conscious of climate change issues, perceived environmental benefits will be the logical outcome [319,323]. However, environmental perceptions may prove negative when adverse impacts are anticipated, such as air pollution [342,343], increased water scarcity, or land spoilage [47,82,115].

Critically, 'blue' hydrogen production relies on steam methane reformation and CCS [344], which could give rise to environmental opposition due to reliance on natural gas [59,345,346]. Additionally, public resistance may develop due to potential resource scarcity and energy injustices associated with the mining of critical materials for green hydrogen production via electrolysis [347,348]. Accordingly, environmental perceptions may also contribute directly to a mix of perceived costs and risks linked to socio-economic impacts. Nevertheless, in the German context, Hoffmann and colleagues [349] demonstrated that German respondents express higher support for green hydrogen when the focus is solely on the benefits of climate protection, as opposed to energy security and climate protection.

5.2.4. Technological perceptions and comprehensive perceived effects

The motivations, behaviours, and decisions of consumers depend on perceptions of specific technology attributes, and whether the totality of these attributes offers a relative advantage over the incumbent technology [81,251,350,351]. However, technological perceptions are yet to be clearly demarcated in the context of hydrogen homes. Drawing on Rogers' DoI [147], Table 5 provides a starting point for comprehensively examining technological perceptions, in view of the implied temporal dynamics of transitioning to hydrogen homes.

Currently, hydrogen demonstration projects are anticipated in countries such as the UK within the coming years; commencing with trials for a few hundred homes if approved by the government [51,352,353]. To date, opportunities for experimentation by the public have been mostly limited to select project sites such as the Hydrogen Experience Centre in Ellesmere Port, Northwest England [354]. However, the planned trial for Whitby village was cancelled in July 2023 following local opposition, which has setback opportunities to increase the trialability and potential observability of hydrogen homes [355,356].

The status quo of hydrogen energy technologies, especially in the domestic context, may give rise to negative attitudes due to perceptions of technological uncertainty and risk. However, should hydrogen appliances be perceived to have an inherent relative advantage over their natural gas counterparts, technological perceptions would prove more positive and strengthen perceived benefits [272]. Perceptions of relative advantage may stem from expectations for better performance in terms

²⁸ This divergence is attributed to hobs actively shaping the lived experience of domestic energy, whereas boilers are usually concealed or more passively experience [27].

Table 5
Technology attributes influencing domestic hydrogen acceptance.

Perceived technology attribute	Explanation in the context of domestic hydrogen
Relative advantage	<ul style="list-style-type: none">• Consumer perceptions regarding the potential advantages of domestic hydrogen over the incumbent technology (i.e. natural gas appliances)
Complexity	<ul style="list-style-type: none">• Consumer perceptions regarding the ease of operation and effort levels associated with the use of hydrogen boilers and hydrogen hobs
Compatibility	<ul style="list-style-type: none">• Consumer perceptions regarding the fluidity or level of equivalence of hydrogen appliances to the existing socio-technical regime, in relation to both the techno-economic (i.e. infrastructural) and behavioural (i.e. socio-cultural) sides of the transition
Trialability	<ul style="list-style-type: none">• The degree to which hydrogen appliances may be experimented with and experienced by consumers on a limited basis prior to potential adoption
Observability	<ul style="list-style-type: none">• The level to which tangible gains are visible and perceptible for others

Source: Authors' compilation based on [147,174].

of energy efficiency, or link to improved ease-of operation in terms of smart performance and reduced maintenance [272]. At the same, non-functional advantages such as pleasing aesthetics related to product design and materials could potentially increase positivity around hydrogen home appliances.

Consequently, technological perceptions will be shaped by various components related to perceived relative advantage, including performance and effort expectancy, as well as compatibility with existing infrastructure [59] and lifestyles [27] (see Table 5). Technological perceptions will also hinge on risk averseness to changing one's home environment, alongside individual propensity for being an early adopter. As noted by Tran et al. [357] in the context of HFCVs and other alternative vehicles, early adopters may be motivated by a mix of environmental, technological, and financial perceptions, resulting in significant consumer heterogeneity.

5.2.5. Financial perceptions and comprehensive perceived effects

It is highly feasible that micro-economic considerations may largely dictate domestic hydrogen adoption among most households, particularly during times of economic crisis and high energy bills [358]. Accordingly, financial perceptions regarding the purchasing and running costs of hydrogen appliances, as well as potential monetary impacts related to maintenance requirements [26,28], will also inform the balance between comprehensive perceived effects for a given consumer.

Given the potential scope for undertaking cost-benefit analysis, financial perceptions are anticipated to link more strongly to the rational decision-making dimension of domestic hydrogen acceptance. However, under conditions of economic stress and uncertainty, perceptions of potential financial loss could evoke feelings of anxiety and fear, which in turn influence attitudes and market behaviour. Additionally, certain consumer segments may be significantly less predisposed to enacting formal or quasi-calculations in the domain of energy appliances, which would render the decision more intuitive and emotive, as opposed to reasoned and rational.

To some extent, consumers may expect to incur additional costs if upgrading to higher performing appliances and could potentially accept these costs if predisposed to being early adopters [271]. Early adopters, who often hold pro-environmental attitudes [359,360], may prove more likely to accept a premium for switching to low-carbon home appliances. In such a scenario, negative perceptions of financial impacts may be partially offset due to a positive cost-benefit appraisal linked to environmental benefits [319]. By contrast, for consumers making up the early or late majority of adopters [147], financial perceptions may align more strongly to the negative side of perceived effects, especially when fuel poverty risks are imminent.

Negative perceptions would also prove more dominant if the relative advantage of hydrogen technologies is not substantiated, or under conditions where alternative technologies such as heat pumps and induction hobs succeed in outperforming hydrogen appliances, while also proving price competitive. As a result, financial perceptions and associated willingness-to-pay for domestic hydrogen will reflect both normative beliefs [255] and market dynamics [59,271], in addition to one's specific economic status at a given point in time [26].

5.2.6. Rational thought and emotional response

In a critical contribution to the energy acceptance literature, Michelsen and Madlener [81] examined the 'motivational factors' influencing the adoption decisions of German homeowners in the context of low-carbon residential heating systems. Through principal component analysis, the study identified 25 factors categorised to six dimensions, which see adoption motivation link to rational decision-making and emotional factors [81]. On the one hand, the framework internalised cost factors (i.e. FP) and implications of a government grant (i.e. FP, ST, CPE), which better reflect the dimension of rational thought. At the same, emotional aspects were represented by proxy in relation to comfort considerations of the technology (i.e. TP). Furthermore, cognitive and affective dimensions may be activated when reacting to external threats, such as environmental or energy supply security considerations (i.e. CPR, CPC), and safety-related risks (i.e. SP).

Interestingly, the critical review conducted by Scovell [82] draws attention to a range of salient beliefs hypothesised to influence emotional responses to hydrogen energy technologies. However, the more recent qualitative study conducted by Scovell and Walton [115] via focus group discussions with Australians reflects the potential for overlooking or obscuring 'hydrogen-related emotions'. Notably, the research angle focuses on how consumers develop 'informed beliefs about hydrogen technologies', however, the thematic analysis fails to reflect the trust dimension of attitudinal acceptance [115].

In summary, Scovell and Walton [115] identified eight categories underpinning attitudes towards hydrogen in general, which fall more strictly across the cognitive dimension of acceptance.²⁹ Countering this perspective, the DHAM posits that the causal chain between salient beliefs, attitudes, and behaviours cannot be decoupled from emotional response, which may include paradoxical feelings towards hydrogen homes.

Ten years on from the contribution of Michelsen and Madlener [81], few sustainability transitions scholars have attended to the emotional aspects of energy acceptance [267,311,361], rendering this dimension heavily underexplored in comparison to cognitive and perceptual factors (see Fig. 16). In response, Martiskainen and Sovacool [361] recently argued that certain low-carbon technologies exhibit 'emotional resonance' that exceed their functional attributes. Critically, the authors highlighted that a focus on emotions challenges many established conceptual frameworks within the field of energy acceptance; calling for adaptations, extensions, and enhancements "to accommodate the potential salience of emotions" [361].

Internalising observations from different research streams, the DHAM posits a direct focus on cognitive beliefs and feelings [337] as the antecedents of domestic hydrogen acceptance and subsequent adoption potential, thereby moving towards an integrated research approach.

6. Conclusions

This review of technology acceptance theories, and empirical studies

²⁹ Uncertainty and unproven technologies (i.e. TP); safety and risk perceptions (i.e. SP and CPR); economic opportunities (i.e. CPB); (in)efficiency and cost (i.e. TP, FP, CPC); (positive) environmental impacts (i.e. EP, CPB); energy security (i.e. CPB); hydrogen competing with other renewables (i.e. TP, CPC); and water use (i.e. EP, CPC).

on hydrogen and domestic energy acceptance, is motivated by the need to develop a comprehensive framework for understanding consumer behaviour in the context of hydrogen homes. As a nascent technology, the emerging contours of domestic hydrogen acceptance remain underexplored [323], while the wider literature reflects an underlying deficit in developing integrated acceptance frameworks.

Critically, the research direction has yet to shift towards a more multi-dimensional focus on domestic energy acceptance (see Fig. 17), as advocated for Bögel et al. [247], Elmustapha et al. [245], and most recently, Chadwick and colleagues [242]. This status quo is striking given that Venkatesh et al. [88] established the higher predictive power of operationalising an integrated model via the UTAUT some two decades ago. Moreover, the advantages of leveraging multi-dimensional conceptual frameworks have been consistently corroborated in consumer acceptance studies focused on computer technology innovation [89], smart home technologies [211,362], solar PV panels [284] and water heaters [245], and more recently, HFCVs [254], among other examples.

6.1. Contributions of the study

In response, the primary contribution of this study is to advance a unified theory of domestic hydrogen acceptance, which can serve as a baseline model for future research. Foremost, the developed model accounts for a wide range of perceptual antecedents of domestic hydrogen acceptance and adoption, in addition to knowledge, awareness, and trust. These constructs are hypothesised to have causal links to both rational thought and emotions, reflecting the cognitive and affective dimensions of attitudinal acceptance and subsequent behavioural response. In addition to providing a robust starting point for future research on domestic hydrogen acceptance, the model offers in-built transferability to examine other low-carbon residential energy technologies such as heat pumps, smart appliances, and solar homes.

This study also makes a methodological and empirical contribution by synthesising findings from hydrogen acceptance and domestic energy acceptance studies for the first time, while benchmarking research approaches against the 5D-DHAF to examine multi-dimensionality across studies. As a result, this analysis reinforces the call for developing and applying integrated theoretical frameworks in energy acceptance studies, while seeking theoretical and methodological pluralism where viable. Moreover, the DHAM provides a direct means for increasing the predictive power of hydrogen acceptance models to support strategic decision-making on decarbonising the residential sector.

6.2. Shifting the research focus towards PLS-SEM

Robust research efforts are needed to explore theories of low-carbon energy acceptance across the mix of technologies examined within this sample, which can be best supported via PLS-SEM [363,364]. As reported in Figs S5 and 16 studies in the sample employed PLS-SEM, including nine studies published between 2022 and 2023. Notably, researchers have recently employed PLS-SEM to identify the salient constructs of consumer acceptance for HFCVs in the Indian context [254, 255,269,277]. These developments signal the emerging research trajectory and motivate the need for disseminating PLS-SEM to the hydrogen research community.

As a variance-based modelling approach, PLS-SEM is well-suited to situations of high complexity where limited theory formation has been established [365], thereby serving as a ‘causal-predictive’ technique [366]. PLS-SEM offers a suite of analytical tools for advancing quantitative engagement with domestic hydrogen acceptance. Foremost, scholars can engage with the DHAM by using software such as SmartPLS [367] to explore the antecedents of supporting or rejecting hydrogen homes, and whether consumer perspectives are shaped primarily by rational decision-making or emotions, or a combination thereof. In doing so, practitioners will be able to test the in-sample and

out-of-sample predictive power of the DHAM [368,369] or specific components of the model [319].

Beyond assessing traditional metrics such as structural path coefficients, effect size, and predictive power, researchers can evaluate the effects (i.e. importance) and performance of indicators through an importance-performance map analysis (IMPMA) [370]. For example, via the IMPMA, a latent construct such as comprehensive perceived benefits (CPB) can be further evaluated in terms of its indicators, such as perceived economic, social, and environmental benefits [319]. In parallel, the mediating role of perceived effects (i.e. CPR, CPC, CPB) and other constructs (e.g. OK, SK) can be tested to validate whether the model supports full mediation, partial mediation, complementary partial mediation, competitive partial mediation, or no mediation [371, 372].

Additionally, Dul [373] developed necessary condition analysis (NCA) as methodology for identifying the necessary conditions for achieving a target outcome.³⁰ By integrating NCA into PLS-SEM when testing the DHAM, researchers can “identify the (‘must-have’) factors required for an outcome, that is necessity logic, as well as the (‘should-have’) factors that contribute to a high-level, namely additive sufficiency logic” [374]. The practical implications of NCA are substantial in promoting more actionable insights for policy makers and stakeholders [374], which can be understood alongside results from IMPMA [375].

Above all, NCA provides a direct means for verifying which acceptance/adoption constructs may presents bottlenecks [373,376] for supporting the deployment of hydrogen homes. Critically, the research community should internalise these suggestions with a view to comparing the predictive capabilities [368] of different hydrogen acceptance and adoption models via PLS-SEM, alongside complementary tools such as machine learning [377,378] and artificial neural networking [379,380].

Finally, data triangulation via mixed-methods analysis [381] can help support a more holistic assessment of the salient factors of domestic hydrogen acceptance [82,115]. By leveraging quantitative insights from qualitative datasets [382–384], results from the SLR conducted in this study (see Fig. 16) can be empirically validated to develop a typology of domestic hydrogen acceptance. As a proven method in the fields of psychology and sociology [385], acceptance typologies (i.e. hierarchical grouping of data into categories of importance) [385,386]) have been applied with efficacy to the context of renewable energy acceptance [387–391].

Testing, adapting, and extending the DHAM, would mark a definitive turning point in advancing understanding of energy acceptance, as witnessed historically via the evolution of the TAM. As an interim step, subsequent exploration could be carried out by conducting a weight and meta-analysis [102] on the retrieved sample (N = 75) or a larger dataset. A weight and meta-analysis can help validate the causal order of variables [109] for predicting domestic hydrogen acceptance and adoption. Notably, Neves et al. [79] employed this approach to determine the main antecedents of adopting sustainable energy technologies using 44 articles and 48 datasets.

Following the tradition of the UTAUT, this study leverages insights from an integrative, comparative review, grounded in systematic methods, to conceptualise a novel framework for examining consumer perceptions of domestic hydrogen. To accelerate the promise of net-zero homes, a paradigm shift in energy technology acceptance research is needed, while radical shifts across industry, supply chains, the labour force, and policy making are required in parallel [392]. As the hydrogen economy evolves, the DHAM suggests that a true litmus test of social acceptance rests with evaluating socio-psychological, cognitive, and

³⁰ The method was originally discussed in the organisational context wherein determinants such as resources and efforts can drive a goal such as better company performance [373].

emotional dimensions of human perceptions in parallel. Internalising this notion can help overcome socio-technical barriers [59] to support the evolution of a sustainable hydrogen future.

CRedit authorship contribution statement

Joel A. Gordon: Conceptualisation, Investigation, Data curation, Data analysis, Conceptual Framework, Visualisation, Writing – original draft, Writing – review & editing. Nazmiye Balta-Ozkan: Conceptualisation, Writing – review & editing, Supervision. Seyed Ali Nabavi: Writing – review & editing.

Data availability statement

Data sharing not applicable no new data generated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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Appendix A. Supplementary data

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