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Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition

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ABSTRACT

Decarbonization in several countries is now linked to the prospect of implementing a national hydrogen economy. In countries with extensive natural gas infrastructure, hydrogen may provide a real opportunity to decarbonize space heating. While this approach may prove technically and economically feasible in the long-term, it is unclear whether consumers will be willing to adopt hydrogen-fueled appliances for heating and cooking should techno-economic feasibility be achieved. In response, this paper develops an analytical framework for examining hydrogen acceptance which links together socio-technical barriers and social acceptance factors. Applying this framework, the study synthesizes the existing knowledge on public perceptions of hydrogen and identifies critical knowledge gaps which should be addressed to support domestic hydrogen acceptance. The paper demonstrates that a future research agenda should account for the interactions between acceptance factors at the attitudinal, socio-political, market, community, and behavioral level. The analysis concludes that hydrogen is yet to permeate the public consciousness due to a lack of knowledge and awareness, owing to an absence of information dissemination. In response, consumer engagement in energy markets and stronger public trust in key stakeholders will help support social acceptance as the hydrogen transition unfolds. Affordability may prove the most critical barrier to the large-scale adoption of hydrogen homes, while the disruptive impacts of the switchover and distributional injustice represent key concerns. As a starting point, the promise of economic, environmental, and community benefits must be communicated and fulfilled to endorse the value of hydrogen homes.

1. Introduction

Since the idea of a global 'hydrogen economy' [1] was introduced in the 1970s [2], the hydrogen revolution has been met with a series of 'false dawns' [3]. Despite past setbacks, the ensuing threat of climate change has propelled renewed action towards achieving this holy grail of the energy transition [4]. Around the world, hydrogen technologies are increasingly recognized as critical for securing a decarbonized future [5]. Accelerated policy action is underway in several countries [6,7] as reflected by the emergence of national hydrogen strategies [8–12].

Australia's National Hydrogen Strategy was released in November 2019 [8]; setting out 57 recommendations for the government, arguably with a stronger focus on economic goals than climate targets [13]. The European Commission (EC) released its *hydrogen strategy for a climate-neutral Europe* in July 2020 [14], while policy developments are underway in several western European countries [15]. In the build-up to the 26th United Nations (UN) Climate Change Conference of the Parties (COP26) in Glasgow [16], the UK made clear its hydrogen ambitions. The Scottish Government released its *Hydrogen Policy Statement* at the end of 2020 [17], with the *UK Hydrogen Strategy* published in August 2021 [18], ahead of the *Heat and Buildings Strategy* in November 2021 [19]. Ultimately, strategic decisions on the role of domestic hydrogen in the UK are set to be taken in 2026 based on a larger evidence base, which includes results from a hydrogen neighborhood by 2023 and village trial by 2025 [19].

Alongside national strategies, international initiatives and partnership agreements are strengthening research and development (R&D) capacity, and the investment landscape for the global deployment of renewably produced hydrogen [20]. Notably, Mission Innovation (MI) is leading the charge to deploy at least 100 "large-scale integrated clean hydrogen valleys" worldwide this decade [21]. Conservatively, the advent of a global hydrogen economy appears set in motion to support climate change mitigation [22,23], with strong prospects also emerging in the Asia-Pacific region [24]. Importantly, the hydrogen transition promises energy security benefits for countries that can secure a first

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Abbreviations

ASHPs	Air Source Heat Pumps
ARENA	Australian Renewable Energy Agency
BEIS	Department of Business, Energy & Industrial Strategy
BP-IC	BP-Imperial College
CCC	Committee on Climate Change
CHP	Combined Heat and Power
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
COP	Climate Change Conference of the Parties
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
DGA	Decarbonised Gas Alliance
EC	European Commission
ENGOs	Environmental Non-Government Organizations
FCVs	Fuel Cell Vehicles
GAD	Gas Appliance Directive
GDNO	Gas Distribution Network Operator
GHG	Greenhouse Gas
GWP	Global Warming Potential
GSHPs	Ground Source Heat Pumps
HESs	Hydrogen Energy Systems
HET	Hydrogen Energy Technology
HFCEVs	Hydrogen Fuel Cell Electric Vehicles
HFCVS	Hydrogen Fuel-cell Vehicles
HFS	Hydrogen Fueling Station
HSE	Health and Safety Executive
IGEM	Institution of Gas Engineers and Managers
kgCO2,eq/MWh	Carbon dioxide equivalent in kilograms per megawatt hour
LCA	Life Cycle Assessment
MCDM	Multi-Criteria Decision-Making
MI	Mission Innovation
MPs	Members of Parliament
MSW	Municipal Solid Waste
NIMBY	Not-In-My-Back-Yard
NO_X	Nitrogen Oxides
N_2O	Nitrous Oxide
OFWs	Offshore Wind Farms
Ofgem	Office of gas and electricity markets
O3	Ozone
PtG	Power-to-Gas
RESs	Renewable Energy Resources
RETs	Renewable Energy Technologies
R&D	Research and Development
SMR	Steam Methane Reformation
SEM	Structural Equation Modeling
SVTs	Standard Variable Tariffs
UN	United Nations

mover advantage, especially those with extensive renewable energy resources (RESs) [25,26].

Despite cause for optimism, technical factors [27,28], market dynamics [29,30], the political environment [28,31], as well as the underlying socio-cultural landscape [32] could constrain national and global objectives for the hydrogen economy. Evidence suggests that cultural and behavioral barriers may stall climate change action at the community and household level [33–35], weakening the prospect of securing low-carbon 'energy futures' [36]. However, in the context of Hydrogen Energy Systems (HESs), end-users have mostly been perceived as a barrier to deployment, or otherwise regarded as another parameter for assessment, as opposed to "a resource for the design" of the system [37]. This characterization overlooks the importance of understanding the dynamics of social acceptance for enacting desirable energy transition pathways [38].

Adopting a socio-technical systems perspective [39,40] this paper contends that public perceptions will largely dictate whether the hydrogen transition is supported by a requisite level of social acceptance, which may prove equally important as technological feasibility [12,41]. It follows that the "human dimension" of the hydrogen transition must go hand-in-hand with "technical logistics" to enable the adoption of hydrogen home appliances [42]. Inadequate levels of social acceptance may very well present the greatest barrier to the realization of the global hydrogen economy [43].

1.1. Socio-technical systems thinking for hydrogen homes

Geels' seminal contribution [44] shifted the analytical focus from "sectoral systems of innovation and production"[1] [45] to a socio-technical systems perspective, which better accounts for the role of end-users in the coevolution of technology and society. In response, researchers have increasingly adopted a socio-technical transition framework approach [46–51] to analyze the ways in which concrete (i.e. the 'physical', 'material' and 'technical' [52]) and abstract factors [53] may influence the speed and duration of the energy transition [54]. Although the broader hydrogen transition has been examined through this lens [55–59], few studies have concentrated exclusively on the prospect of 'hydrogen homes'; composed of hydrogen-fueled appliances for domestic space heating, hot water and cooking [60].

As with natural gas-based appliances [61], and other large-scale energy systems [62–64] that serve the needs of society [65], the socio-technical system for hydrogen homes will be sustained by a range of interdependent factors, which may determine the pace and nature of the transition. Although the emerging literature on the feasibility [66,67] and determinants of domestic hydrogen acceptance [42,68,69] recognizes that a range of socio-technical barriers exist, limited critical analysis has been undertaken to unpack the significance of these findings. While the domestic hydrogen transition faces a distinct set of socio-technical barriers which may be viewed differently across parts of society, there is a significant knowledge gap concerning how and why perceptions may vary at the community and household level. In response, this paper answers the call to increase social science engagement with consumer preferences for hydrogen homes [60,70–72].

As a first step towards addressing this knowledge gap and elevating the role of end-users in hydrogen homes, this article sets out to determine what is currently known and what needs to be understood about barriers to social acceptance in the future if candidate countries are to deploy hydrogen homes at scale. Accordingly, the aims are as follows: (1) to analyze, through literature review, the key socio-technical factors shaping public perceptions of the domestic hydrogen transition; (2) to rank the critical factors of domestic hydrogen acceptance; and (3) to map a future research agenda for overcoming barriers to domestic hydrogen acceptance.

Following this introduction, Section 2 describes the methodology and charts the literature on public perceptions of the domestic hydrogen

[1] Malerba [45] defines a sectoral system as "a set of products and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products.".

transition. Section 3 presents the theoretical approach employed in this study based on the five dimensions of domestic hydrogen acceptance, as visualized in Fig. 3. Applying this analytical framework, Section 4 synthesizes the existing literature on public perceptions of socio-technical barriers to the domestic hydrogen transition. Next, Section 5 provides a ranking of the critical factors of domestic hydrogen acceptance and maps a future research agenda to help accelerate the social acceptance of hydrogen homes. The concluding section highlights the key findings and contribution to the energy transitions literature.

2. Materials and methods

Following Sovacool et al. [73] and Scovell [12], this paper undertakes a structured narrative review by applying specific search criteria to explore the literature on domestic hydrogen acceptance. A narrative review aims to identify and summarize previous publications, while highlighting new study areas yet to be addressed [74]. Social science research on domestic hydrogen is a subset of the wider literature on hydrogen acceptance [73], which this study draws on as supporting evidence to the case of hydrogen homes. This approach is consistent with the underlying objective to map a future research agenda by synthesizing the existing evidence base. A more systematic literature review could not be undertaken due to the relatively small sample size (N = 17), however, the initial scoping and screening procedures followed systematic methods.

There is an emerging body of literature focused on the social acceptance of hydrogen appliances for home use and the acceptability of domestic hydrogen in the broader energy transition [60,71,72,75,76]. However, the number of peer-reviewed articles on 'hydrogen social acceptance' remains dwarfed by studies on the 'hydrogen economy' and 'renewable hydrogen' [77]. Moreover, to date, hydrogen acceptance research has engaged almost exclusively with transportation applications [68,77], consisting mainly of studies focused on trials/demonstrations of hydrogen fuel-cell vehicles (HFCVS), and associated infrastructure [71,77,78] such as hydrogen fuel stations [12]. While this literature has a comparatively rich base of international research on public perceptions [68,77] dating back to the 2000s [79–84], studies on domestic hydrogen acceptance are a recent development, pioneered mainly by researchers in the UK, Australia, and parts of Europe [68–70, 85–87].

Emodi et al. [71] systematically reviewed the literature on hydrogen acceptance, retrieving 43 valid articles for the period 2008–2020, which included five papers on domestic hydrogen [58,66,73,87,88] since 2018. More recently, Scovell [12] reviewed 27 quantitative studies exploring the relationship between psychological factors and Hydrogen Energy Technology (HET) acceptance. The study underscored the need to examine hydrogen acceptance factors and moreover, the reasons and extent to which acceptance levels vary between people. Elsewhere, Kar et al. [78] used bibliometric analysis to analyze 1275 articles published between 2016 and 2020, showing that research on the "hydrogen economy" has accelerated, with the phrase gaining better acceptance in Asian countries. Adopting a socio-technical systems approach, Griffiths et al. [39] carried out a critical and systematic review of industrial developments regarding low-carbon hydrogen. Additionally, Edwards et al. [90] undertook a multi-disciplinary review focused on "the status of hydrogen technologies in the UK," calling for further research focused on public acceptance.

This study set out to retrieve the full evidence base on domestic hydrogen acceptance from across the academic and grey literature to provide a state-of-the-art review. The following sections explain the data collection procedure, which involved accessing articles from the four databases: Scopus, Web of Science, the Hydrogen Knowledge Centre, and Google Scholar. The search resulted in a total of seventeen studies for final review (see Fig. 1).

2.1. Scopus and Web of Science

Using the Scopus database, an initial search was carried out with the following key words: "hydrogen heating" OR "hydrogen acceptance" OR "hydrogen homes." The search returned only 76 results, whereas a subsequent search with the phrase "hydrogen transitions" returned 128 results. Given the relatively low numbers, a further search was implemented following Emodi et al. [71]: "social acceptance" OR "public acceptance" OR "consumer acceptance" OR "household acceptance" AND "hydrogen." This search was successful in returning 241 results. A parallel search using the key words "hydrogen transitions" OR "hydrogen acceptance" OR "hydrogen heating" OR "hydrogen cooking" OR "hydrogen homes" also returned 241 results.[2]

Screening the first 241 articles (based on Emodi et al. [71]) retrieved just one study on hydrogen acceptance in 2015 [91], compared to four studies in 2016 [92–95]. Given this trend, the date filter was reset to 2016 (N = 105). Three more studies on hydrogen acceptance were retrieved from 2017 [89,96,97], of which Oltra et al. [89] included a focus on stationary home fuel cells. A further 18 studies were retrieved with a relevant framing on hydrogen acceptance [12,24,43,71,98–111], however, none of these focused on domestic applications. Screening the remaining 241 articles based on the second key word search ("hydrogen transitions" OR "hydrogen acceptance" OR "hydrogen heating" OR "hydrogen cooking" OR "hydrogen homes") located two studies in 2016 [112,113].[3] From 2017 onwards, three papers on hydrogen acceptance were retrieved, with two including an explicit focus on the residential sector [60,75].

Given these results, a follow-up search was carried out in Web of Science with the date filter set to 2017, using the term "hydrogen acceptance" in the Title, Abstract or Author Keywords, which provided 276 results. The breakdown underscored the dominance of technical literature on hydrogen technologies and the deficiency of studies on social acceptance aspects. The top six categories defined by Web of Science ('Energy Fuels,' 'Chemistry Physical', 'Electrochemistry', 'Materials Science Multidisciplinary', 'Environmental Sciences', 'Chemistry Multidisciplinary', and 'Green Sustainable Science Technology'), represented 89% of the search results (N = 247). With the removal of any duplicates, five studies passed the screening criteria for further consideration [114–119]. Although valuable as supporting evidence, none of these studies provided a specific focus on domestic hydrogen acceptance.

2.2. Hydrogen Knowledge Centre

Given the limited number of studies retrieved from Scopus and Web of Science, a subsequent search was conducted using the Hydrogen Knowledge Centre database[4]; a digital resource hub launched in March 2021 by the Institution of Gas Engineers and Managers (IGEM) to support understanding of the hydrogen transition. The repository provides access to nearly 3000 sources on hydrogen (in English) and responds to the need for a "|hydrogen industry knowledge-sharing platform" [120].

Selecting the key words "Consumer & End Users" and "Hydrogen for Domestic Applications" from the drop-down menu produced 129 results, dominated by studies in the United Kingdom (N = 64) and Australia (N = 21). The titles and abstracts were carefully screened to source the first available study with a definitive focus on domestic hydrogen acceptance; published in November 2018 and commissioned by the Committee on Climate Change (CCC) [121]. One month later, the Australian Renewable Energy Agency (ARENA) released a report on public perceptions of hydrogen for energy, which included a focus on domestic heating and cooking [68]. Overall, the Australian public appeared to be

[2] No duplicates were reported.
[3] Resetting the data filter to 2016 reduced the search results to N = 51.
[4] https://www.igem.org.uk/hydrogen-knowledge-centre/.

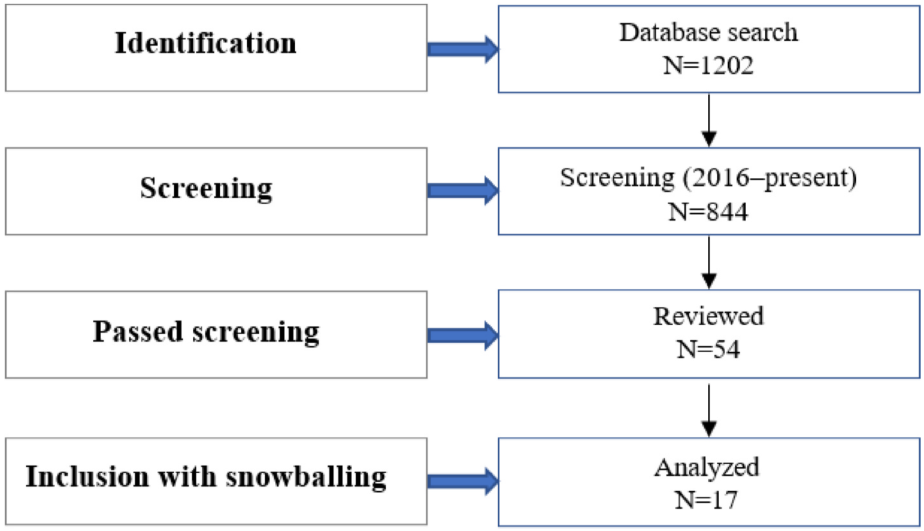

Fig. 1. Data collection procedure.

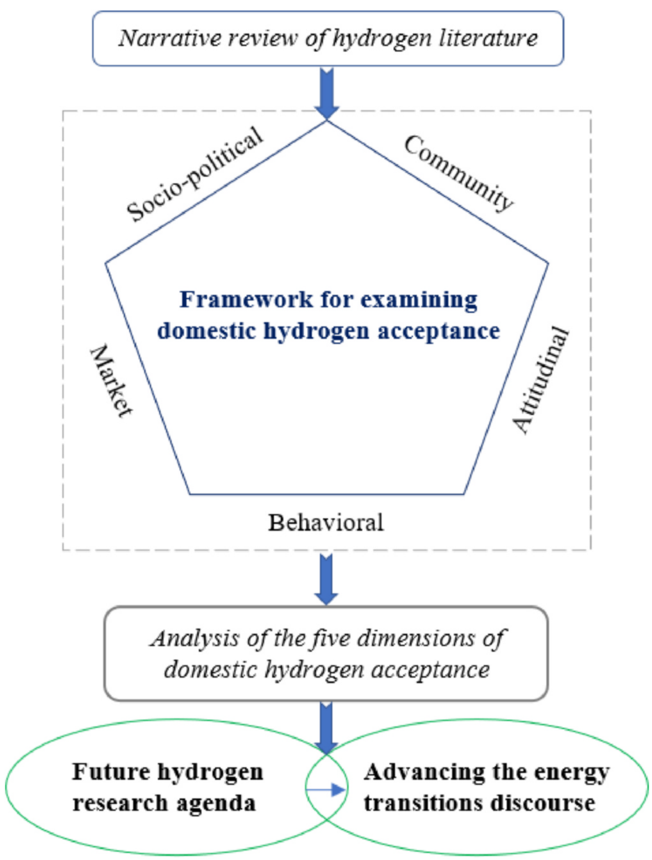

Fig. 2. Research procedure and methodology.

"positively cautious" about developing a national hydrogen industry and economy [68].

Refining the search to English studies published since November 2018 produced 97 results.[5] At the end of the screening, nine additional studies had been retrieved, six of which presented primary data on domestic hydrogen acceptance as required for final inclusion [42,68,69,87,88,122]. While this database search proved fruitful, the last study dated to June 2020 [69], which suggested more recent literature could still be retrieved.

2.3. Google Scholar and snowballing

Two final key word searches were performed in Google Scholar with the filter "2017 to present": "hydrogen transitions" (N = 236); and "hydrogen transitions" OR "hydrogen acceptance" (N = 315). Given that the second search term increased the results by 33%, these studies were scanned. In total, seventeen studies passing the first screen [31,37,39,70,72,78,90,117,123–131]. Of note, Martin et al. [37] reviewed 152 publications on HESs using a human-technology relationship framework. The authors called for more research on hydrogen use in the residential sector, with a shift towards a more user-focused approach to design a desirable hydrogen system, as opposed to making the system acceptable to consumers following technology deployment. However, this search returned limited results on domestic hydrogen acceptance once duplicates were removed, namely four studies [70,72,123,128].

Encouragingly, purposeful snowballing sampling [132] helped retrieve three additional studies [76,77,86]. Further analysis revealed the following connections [12,77]: are studies from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia [86]; is ARENA's follow-up study to Refs. [68,76] directly followed [89] with a focus on hydrogen acceptance in Europe; three UK studies [60,75,87] are authored by Scott and Powells (Newcastle University); while [69,123] are studies from Leeds University and Leeds Beckett University, respectively, which follow technical work on the Leeds City Gate H21 project [66]. This snapshot reveals a degree of continuity in domestic hydrogen studies (see Table 1), but also limitations in research diversity and scope.

In addition to the studies presented in Table 1, this paper draws on extensive evidence from the literature on renewable energy (RE) acceptance [85,133–140], energy justice [141–146], and 'hydrogen futures' [29,55,57–59,147]. This literature helps contextualize the findings on hydrogen acceptance within the broader energy transitions discourse [148–150]. To derive an analytical framework grounded in theories from the behavioral and social sciences (see Fig. 2), the paper integrates scholarly contributions to 'the triangle of social acceptance of renewable energy innovation' [135] and Social Practice Theory [151], as well as the Energy Justice [145] and Energy Cultures framework [152].

[5] The distribution of studies was almost equal for each of the keywords.

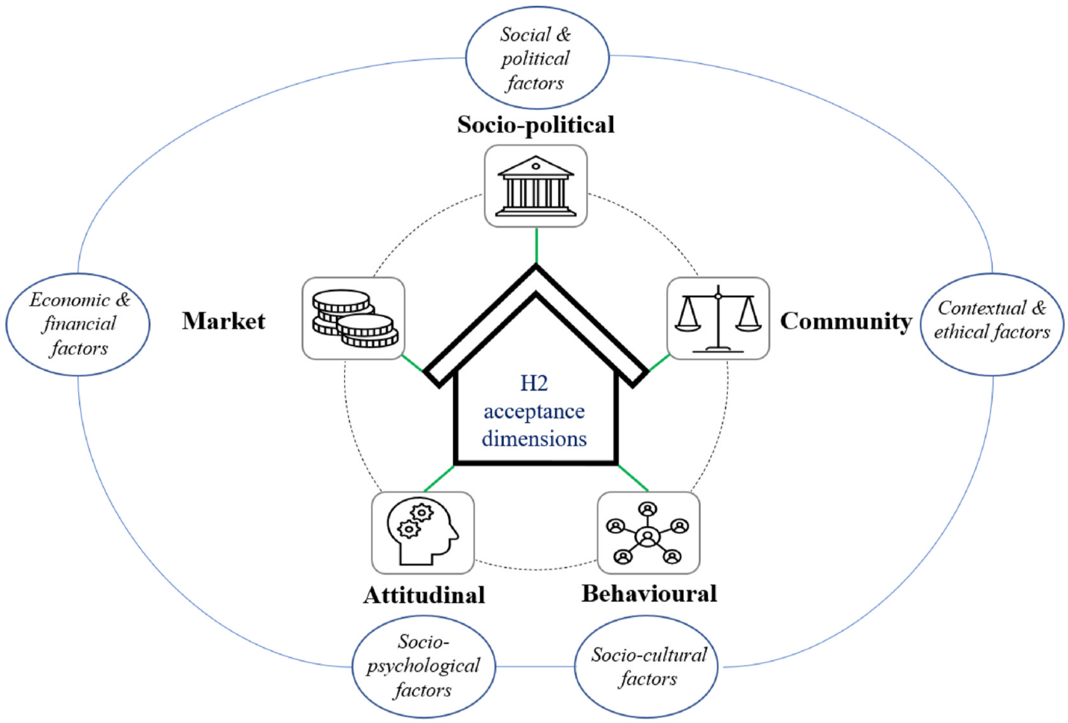

Fig. 3. Analytical framework linking dimensions and factors of domestic hydrogen acceptance based on Gordon et al. [153]. The framework links together the five dimensions of domestic hydrogen acceptance with their corresponding factors.

3. Socio-technical barriers and the five dimensions of hydrogen acceptance

Based on the work of Gordon et al. [153,154],[6] this section describes the proposed theoretical approach for examining socio-technical barriers to domestic hydrogen acceptance (see Fig. 3). Through mapping respective barriers to attitudinal, socio-political, market, community, and behavioral acceptance, the analytical framework contributes to socio-technical systems thinking [44] on the energy transition [62,63], and answers the call to elevate the role of end-users in HESs [37].

3.1. Attitudinal acceptance

Attitudinal acceptance operates at the micro-scale configured by factors such as knowledge, awareness, perceptions, and attitudes [85,133], each of which play a part in shaping how end-users perceive the costs, benefits, and risks associated with sustainable energy technologies [133]. Perception can be defined as what consumers think or associate with hydrogen technologies, whereas attitude represents a more definitive judgement about whether a hydrogen transition is desirable [83].

At present, the benefits of domestic hydrogen remain poorly understood by end-users [121] due to low levels of knowledge and understanding [155]. Furthermore, when consumer benefits are tied up with abstract environmental gains related to climate change mitigation, individuals are more likely to prefer the 'least-worst' option or to otherwise remain indifferent [121]. Such a scenario would inhibit a transition to domestic hydrogen, as active consumer acceptance is more likely to support the uptake of low-carbon heating technologies [134]. In turn, attitudinal acceptance is evaluated by gauging public knowledge and awareness of hydrogen, safety perceptions, affective response, and the impact of information on consumer attitudes.

[6] Ref. [153] is currently under review by Applied Energy. Ref. [154] was accepted as a conference paper for the 13th International Conference on Applied Energy (ICAE) and has been invited to the *Special issue*, SI:ICAE 2021.

3.2. Socio-political acceptance

As a key component of the "dynamic political feasibility space" of decarbonization pathways [156], socio-political acceptance is contingent on the ability of regulators, legislators, policymakers, and other key stakeholders to craft effective national policies to foster community, market, and public acceptance of renewable energy technologies (RETs) [135,136]. Trust, fairness, and legitimacy have been identified as key factors of socio-political acceptance [135,157], which broadly reflect the preference for a 'just energy transition' [123,141,142]. As stated by Aditiya and Aziz [24], "public trust determines the severity of social friction that may heavily influence the hydrogen program."

Socio-political acceptance for an emerging technology such as domestic hydrogen can be considered as an extension of broader acceptance for renewable and low-carbon energy technologies, including other hydrogen applications such as fuel cell vehicles (FCVs). To an extent, hydrogen acceptance can be extrapolated from the public's general disposition towards the net zero agenda. Accordingly, socio-political acceptance is firstly considered in terms of consumer engagement and trust in the energy transition. Thereafter, public perceptions are examined in relation to hydrogen production methods, decarbonization pathways, environmental impacts, and trust in key actors and stakeholders.

3.3. Market acceptance

Sovacool and Ratan [136] explain market acceptance according to the interactions between investors as technology supporters and consumers as technology adopters, which plays out "at a meso level between national politics and local communities." It follows that market acceptance for domestic hydrogen end-users will depend on both macro- and micro-scale factors. Additionally, appliance development will depend on international markets as countries compete for a frontrunner advantage in the global hydrogen economy [31].

Market acceptance at the macro-scale is shaped by economic impacts across the national, regional, and local levels. In contrast, market

Table 1
This table provides a summary of social science research on domestic hydrogen acceptance. In total, 17 studies were retrieved since 2017. Nine studies were carried out in the UK, five in Australia, and three in Europe. Twelve items belong to the grey literature, five are journal publications, and one is a thesis paper. Eleven of the studies focused on domestic hydrogen acceptance, while seven items provided selective findings within the context of the broader hydrogen transition.

Study	Location, research type, and sample size	Research scope
[89]	Nationally representative only survey using quota sampling EU: Belgium, France, Germany, Norway, Slovenia, Spain, UK; N = 7148	Analyzes public attitudes towards stationary residential fuel cells (micro-combined heat and power (CHP)) and hydrogen fuel cell electric vehicles (HFCEVs) to understand cross-country variations.
[76]	Nationally representative only survey using quota sampling EU: Belgium, France, Germany, Norway, Slovenia, Spain, UK; N = 7148	Examines attitudinal acceptance by analyzing consumer and citizen reactions to information provision on hydrogen fuel cell technologies.
[121]	a) Nationally representative online survey UK; N = 1029 b) Four focus groups London and Edinburgh; N = 29	Assesses the public acceptability of hydrogen boilers and heat pumps, focusing on attitudinal differences between socio-demographic groups.
[68]	a) Nationally representative online survey Australia; N = 2785 b) 10 focus groups South Australia and Victoria; N = 92	Explores the Australian public's response to the burgeoning opportunities of hydrogen for export, transport, and domestic use; focusing on potential barriers and enablers to a national hydrogen transition.
[77]	Interviews with industry and government representatives from across the hydrogen energy value chain Australia; N = 14	Examines stakeholders' experiences with public perceptions of hydrogen, with the goal of advancing "socially responsible practices and policies" for developing Australia's hydrogen economy; outlining the key issues that could affect the current and future level of acceptance and adoption of hydrogen energy.
[88]	9 focus groups Australia: Queensland (Townsville), Victoria (Warrnambool), and Northern Territory (Darwin);[b] N = 72	Investigates the potential for hydrogen in three regions of Australia and the country more broadly, with a focus on public perceptions and best practice for community engagement.
[123]	a) Online survey Leeds and Teesside; N = 578 (548 from Leeds) b) Semi-structured interviews with key stakeholders purposive sampling; N = 30	Provides a regional perspective of public perceptions regarding the development and use of hydrogen energy technologies as an energy vector to decarbonize processes within and between Leeds and Teesside.
[42]	4 focus groups with consumers from different housing segments connected to the gas grid[a] England: Manchester and Birmingham; N = 39	Assesses consumer perspectives on the disruption and costs impacts of a hypothetical hydrogen switchover, focusing on logistical and welfare issues.
[87]	Nationally representative online survey UK; N = 742	Designs and deploys an online survey, collecting quantitative data on public perceptions of hydrogen and hydrogen blending in the UK.
[60]	Paper-based survey and follow-up interviews (cafés/coffee shops) 10 different locations in the North East of England; N = 100	Examines how the physical and chemical properties of hydrogen may impact the 'gas-energized' social practices of cooking and heating.
[75]	a) Online survey, representative of the HyDeploy2 trial areas North of England; N = 700 b) Paper-based survey conducted in cafés Nine towns in the North of England; N = 102	Elicits and evaluates public perceptions of hydrogen and hydrogen blending in the UK in relation to theories of social practice, energy justice, and place attachment
[122]	a) 50-question online poll UK; N = 2000 b) 4 focus groups North of England and Greater London; N = 32	Examines public opinion on the environment and climate change; and views on changes to home heating, industry, and transport for achieving net zero; explores attitudes towards decarbonization pathways and policy recommendations for home heating, industry, and transport.
[69]	a) Nationally representative online survey UK (Leeds, Monmouthshire, and Birmingham); N = 1027 b) Discovery interviews N = 12 c) Deliberative workshops	Explores public perceptions of changing the UK domestic fuel supply to 100% hydrogen; examines beliefs about the environment, inconvenience and costs, safety, and potential economic impacts.
[86]	Nationally representative online survey Australia; N = 3020	Examines public perceptions towards hydrogen for domestic use (n = 1507), and export and future energy considerations (N = 1513)
[72]	Two-hour online workshop with participants from academia, government, industry, and advocacy organizations Australia; N = 22	Investigates the current knowledge and knowledge gaps regarding the potential impacts of Australia's domestic hydrogen transition on energy vulnerability.
[128]	Online survey Republic of Ireland, N = 115 Semi-structured interviews with survey respondents (N = 8)	Examines how the public perceives hydrogen as an energy vector, outlining potential obstacles to social acceptance.
[70]	Online survey Discrete choice experiment and a mixed logit model France; N = 202	Analyzes consumer preferences for hypothetical hydrogen-based energy storage systems, considering the behavior of households vis-à-vis hydrogen as a new energy carrier, and acceptance of supply and management methods.

[a] Two with owner-occupiers, one with private landlords, and one with a mixture of tenants (private, social, student).
[b] Two focus groups were held with the general public in each city (N = 52) and 1 focus group was held with influential stakeholders in each city (N = 20).

acceptance at the micro-scale focuses on the household level, where willingness to pay for new technologies is largely determined by cost and financial factors. These scales or levels are considered by reviewing how the public perceives issues concerning economic impacts, technology choice, and financial costs.

3.4. Community acceptance

Making a seminal contribution to the conceptualization of social acceptance of RETs, Wüstenhagen et al. [135] explained community acceptance in terms of the willingness of local stakeholders to invest in new energy projects or appliances, which is largely shaped by perceptions of fairness and justice regarding the distribution of costs and decision-making processes. These perceptions are strongly influenced by the provision of procedural and distributional justice, which represent two of the three tenets of the Energy Justice framework [144]. The framework was developed from environmental justice research and is designed to "foster analyses of unfair energy policies and projects" [158].

Procedural justice is determined by the informational aspects of energy developments, decision-making processes, and the degree of stakeholder participation in the planning of rules and laws [143,145,159], whereas distributional justice depends on how the costs and benefits of technology adoption are distributed across society [146,159,160]. Completing the triumvirate [145], recognition justice is concerned with the provision of full and equal political rights as a mechanism to help prevent discriminatory practices and the potential for 'misrecognition' [161], which may take shape through cultural domination, non-recognition, and disrespect [162].

Historically, justice concerns have rarely featured prominently in stakeholder planning processes for energy projects [163]. Notably, the geographic distribution of land-based UK renewables has been associated with issues of social injustice [164], reinforcing the need for inclusive and equitable approaches to managing the hydrogen transition. Furthermore, community acceptance research has often adopted a post hoc approach through case studies on local responses to specific project proposals [137]. While there are benefits to such research, case studies of this nature may overlook key decision-making factors; failing to provide insights on how broader contextual factors impact the views of local communities [137]. Here, community acceptance is explored in respect to public perceptions concerning the spatial dynamics of hydrogen communities and the transition at large, in addition to related issues surrounding distributional and procedural justice, and disruptive impacts.

3.5. Behavioral acceptance

Resonating with the Energy Cultures framework – based on beliefs, values, and energy practices [152] – the 'social practice approach' has been proposed for better understanding the daily practices and behaviors associated with energy technologies [75,165]. Social Practice Theory contends that behaviors are an expression of personal choice dictated by beliefs, values, attitudes, and tastes; equating lifestyle habits to a performance of sorts, wherein behaviors become internalized through repetition or practice [151,166]. In respect to understanding new energy practices, Scott and Powells [60] suggest that the "analytical focus" should be shifted to capture how people are likely to behave, as opposed to what they may think or feel. Following Gordon et al. [153], behavioral acceptance is assessed according to interactions between socio-cultural and personal factors, resting on consumer perceptions of hydrogen's disruptive impacts to daily routines during the switchover period, and subsequent changes to the lived experience of heating and cooking.

4. Results

The following sections (4.1–4.5) provide a comprehensive review of the empirical data on domestic hydrogen acceptance, drawing on supportive findings from across both the hydrogen futures and energy transitions literature. Here, and throughout the rest of the paper, a sequential, structured approach is taken by examining attitudinal, socio-political, market, community, and behavioral factors.

4.1. Barriers to attitudinal acceptance

4.1.1. Perceptions, knowledge, and awareness of hydrogen

Affective or emotional responses to hydrogen have been shown to shape consumer attitudes, especially in respect to risk perceptions [167,168]. Traditionally, the word 'hydrogen' has tended to evoke a neutral response from the general public [68,88,169,170]. Associations to hydrogen may vary from energy, fuel, gas, element, and peroxide, to renewable, water, bomb, balloon, explosion, flammable, or future technology [88,128]. Consumer attitudes may also take on a neutral framing in some cases. For example, Oltra et al. [89] found a high prevalence for neutral attitudes towards hydrogen home fuel cells in the United Kingdom, Norway, and France. 52% of South Koreans (N = 1000) had neutral attitudes towards hydrogen fueling stations [99], while 73% of UK public participants (N = 4673) had no opinion or a neutral opinion prior to a novel public engagement activity for the hydrogen bike [127]. When neutral associations and attitudes do prevail, this may be due to an underlying lack of knowledge and awareness [87].

Evidence suggests that willingness to adopt low-carbon technologies – understood as willingness to use a technology that is available on the market, given that all user-related aspects remain equal in comparison to conventional energy applications [83] – may be positively associated with knowledge and awareness [42]. Indeed, prior knowledge has been shown to be a significant driver of public support for hydrogen technologies [171], especially in the context of hydrogen transportation [172].

It is well-documented that public knowledge and awareness of hydrogen and its potential commercial applications remains low [81,171,173–175]. Despite some parts of the public proving reasonably knowledgeable about hydrogen [83,94], most studies report low levels of knowledge and awareness (see Table 2). Even in Japan where there is a well-publicized effort to develop hydrogen energy infrastructure [176] as part of the country's Strategic Energy Plan [177], public awareness continues to lag compared to RETs and secondary energy sources [97]. Typically, citizens have limited knowledge about hydrogen production methods [69], safety and storage [15], and may still lack any immediate reference point or daily interaction with hydrogen energy technologies (HETs) [178]. The result is feelings of uncertainty, unfamiliarity, and remoteness concerning hydrogen [75,179,180]. Consequently, current perceptions may prove speculative or tentative at best, while the public remains cautious in their judgements and somewhat skeptical about the hydrogen transition [69,84].

Hydrogen's status as a peripheral technology [75] is especially pronounced in the domestic context where it remains unfamiliar to most of the public [42,77]. Scott and Powells [60] observed that the public has limited knowledge about the physical and chemical characteristics of hydrogen. Furthermore, public perceptions may hinge on how the technical complexity and unfamiliarity of hydrogen appliances compare to other low-carbon technologies for domestic heating and cooking [121].

Despite an underlying consensus that hydrogen knowledge and awareness remain low, there are early indications that hydrogen is starting to enter the public consciousness, albeit gradually [70,76,86]. Damette et al. [70] showed that mainstream hydrogen knowledge appears to have increased compared to earlier studies in 2006 [83] and 2010 [171], while Martin et al. [86] found that subjective knowledge of hydrogen has increased in Australia. Furthermore, self-reported knowledge on hydrogen was higher than in 2021 [86] than in 2018 [68] for five out of six statements. Interestingly, self-reported knowledge on hydrogen production was lower [86].

These findings reaffirm the need to communicate more to the public

Table 2
This table provides evidence on public knowledge and awareness of hydrogen. Overall, hydrogen remains an unfamiliar proposition to society, with the public having limited knowledge.

Source	Findings
[60]	• Two-thirds of survey participants were unaware that hydrogen burns with a near invisible flame
[68, 86]	• Australians had low objective knowledge of hydrogen, especially regarding its characteristics and properties (men answered more questions correctly)
[88]	• Only two focus group participants had heard something about Australia's National Hydrogen Strategy, but neither could provide any additional details
[89]	• Less than 10% of European respondents were familiar with HETs • 59% were unaware about hydrogen's role in energy production and only 25% had heard of residential fuel cells
[121]	• 45% of respondents were unfamiliar with hydrogen appliances or heat pumps • Those with knowledge had limited awareness about decarbonization credentials
[123]	• 36% of respondents (the highest proportion) indicated they 'need to know' more about hydrogen to comment about its role in decarbonizing the economy
[181]	• 88% of survey respondents had never heard of hydrogen boilers; compared to 49% for biomass boilers, 61% for ground source heat pumps (GSHPs) and 75% for air source heat pumps (ASHPs)

about the potential or desirable role of different energy sources in developing the hydrogen economy; without forcing consumers to try to 'crack the hydrogen color code' [182], given its ever-evolving rainbow spectrum [183,184]. As a first step towards counteracting this underlying knowledge gap which may otherwise constrain the domestic hydrogen transition, it is strongly recommended that the public is at least provided with a simple explanation of different hydrogen production methods [121].

4.1.2. Hydrogen safety factors

Hydrogen technology remains a contested topic [147] characterized by blurred representations between 'myths' and 'facts' [185], especially in relation to hazards and risks [186]. Despite obvious risks given its flammability characteristics [187], hydrogen fuel has been used safely in aerospace [188,189], and petrochemical applications [190–192] for several decades [186]. Nevertheless, the safety credentials of hydrogen have been long debated [186,191,193,194] in relation to a range of areas and applications [195] including aviation [196,197] surface transportation [198–200], handling and storage [201–204], industrial uses [205–207], and more recently domestic heating and cooking [42, 60,75]. To date, acceptable safety standards have been upheld [185], however, adherence to safety measures is significantly harder to secure and monitor for hydrogen use in residential and commercial applications [208].

While most studies indicate that the safety hazards of hydrogen [195] are roughly equivalent to that of natural gas, gasoline, and other fuels [186,209], it is generally accepted that 'hydrogen blending' – the injection of small quantities of hydrogen into existing natural gas networks [210,211] – will engender potentially new hazards [212]. Hydrogen has distinct physical and chemical properties [60,212], which may present new or greater risks in the domestic environment (see Table 3). Notwithstanding, hydrogen blending has been promoted as a 'practical' and 'non-disruptive' pathway towards securing emissions reduction in residential heating [213].

4.1.3. Public perceptions of hydrogen safety

Hydrogen safety issues extend beyond the technical domain to the socio-cultural dimension, given that the domestic environment is a place of "security and control," which the introduction of new energy technologies should reinforce [219]. Engaging with hydrogen experts and key stakeholders in Germany, Schlund et al. [129] reported a consensus that technical issues, safety concerns, and other risk factors remain a significant barrier to market development and public acceptance of low-carbon hydrogen technologies. Compared to other technologies such as stationary battery storage and biofuel production plants, the public is significantly more concerned about the explosive hazards of hydrogen refueling stations [98], which may lead to opposition on safety grounds especially from households with more family members [99]. Furthermore, hydrogen is often portrayed as a "sensitive gas," which may undermine its status in countries without any direct engagement in hydrogen infrastructure and industrial applications, weakening its role in the global energy transition [78].

Table 3
This table identifies technical barriers to the deployment of domestic hydrogen appliances and describes their safety implications.

Characteristics	Safety implications
Near-invisible, pale- blue flame [214] and odorless [75]	Higher risk of fires remaining undetected or propagating due to reliance on proximity to the flame/appliance for sensory awareness [212]
Higher flame speed than natural gas [215]	Increases the propensity for flame flashback whereby the flame burns closer to the appliance, increasing the risk of spillage of combustible mixture and potential explosion [210,215,216]
Higher adiabatic flame temperature than natural gas [217]	Formation of nitrogen oxides (NOx) increases exponentially with adiabatic flame temperature, resulting in higher levels of respiratory health risks [218]

In some cases, public concerns over hydrogen safety may supersede other issues such as cost and performance [68]. For example, support for converting the Australian gas network to 100% hydrogen was limited to 38% (compared to 30% for electrification), largely owing to public concern about hydrogen's volatility and flammability [68]. While safety concerns over hydrogen blending proved minimal [68], other studies suggest a mixed picture regarding public perceptions of hydrogen safety (see Table 4). Concerns may revolve around personal safety, environmental impacts, the potential for leakages in hydrogen pipelines and the risks associated with carbon, capture and storage (CCS) [122].

Socio-structural variables such as socio-demographic, socio-economic, and socio-cultural characteristics [103], as well as geographic factors and household differences [99,122] may partly explain variation in safety perceptions. For example, the Decarbonised Gas Alliance (DGA) found that focus group participants from Warrington – an industrial town located in the North West of England – expressed few concerns about safety due to an underlying trust in regulatory practices, whereas participants from Bushey – an affluent commuter town in North London – had more reservations about the safety credentials of hydrogen [122]. While one Warrington resident drew a comparison between CCS and nuclear waste, the consensus from the North West was that hydrogen would not be brought online unless it was deemed as safe as natural gas. Other studies suggest that safety concerns are reduced when public trust in regulation is stronger [68,69,87].

In some instances, consumers may be more preoccupied about the safety levels of CCS than the actual use of hydrogen in their homes [122], highlighting the cross-sectoral implications of hydrogen technology and the importance of community acceptance. Additionally, hydrogen boilers may present less of a safety risk in the eyes of consumers due to their self-contained nature, whereas the exposed, yet invisible flames of hydrogen cooking appliances exhibit a more direct and tangible threat to the domestic environment [60]. Accordingly, households may reject hydrogen as a fuel for cooking unless it burns with a visible or detectable flame, since this feature is regarded as

Table 4
This table describes the public's perceptions of hydrogen safety in the UK, Australia, and Europe. Overall, there are mixed views regarding the safety credentials of domestic hydrogen.

Source	Country	Public perceptions of hydrogen safety
[42]	UK	• Most participants felt reassured provided safety tests were carried out. However, concerns remained over several key factors including the combustibility, color and smell of hydrogen gas, hydrogen production and storage
[68]	Australia	• Respondents were mostly unconcerned about the safety risks of natural gas being 'blended' with 10% hydrogen, preferring the use of this term to 'piped' or 'injected'
[75]	UK	• 69% of online survey respondents and 57% of paper survey respondents envisaged no significant impact of hydrogen blending on domestic safety[a] • 35% of paper survey respondents reported positive impacts on safety
[83]	Netherlands	• 70% of respondents would reject hydrogen blending if it proved marginally less safe than natural gas, but still within regulatory limits
[93]	Germany	• Consumers are highly sensitive to the risks associated with hydrogen energy storage

[a] Less than 14% and 8% of participants from the online and paper survey perceived that there would be a negative impact on safety.

paramount to both safety and functionality.[7]

To an extent, negative perceptions of hydrogen could persist due to its iconography with war [167,220] and explosive accidents [221,222], which may prove challenging for some citizens to overlook [223]. However, such attitudes may lie with inflated concerns [77] attributed to a fear of the unknown [15,209], as opposed to more credible fears about hazards and risks [224]. While the importance of socio-structural factors has been illustrated, concerns over hydrogen safety appear to also stem from an underlying lack of public awareness and knowledge [60]. Notwithstanding, to strengthen social acceptance at both the community and household level, it is first necessary to demonstrate that hydrogen technology and infrastructure is technically feasible [208], with a full-scale conversion to hydrogen ensuring at least the same safety levels as natural gas networks [69]. The safe capture and sequestration of carbon should also be proven to avoid the risk of public opposition and costly delays [69].

4.1.4. *Information provision and experience with hydrogen energy technologies*

The provision of information, whether factual [225] or hypothetical [42], can have a significant impact on how participants perceive climate change [226] and energy technologies [227] including hydrogen [86]. Information provision may motivate consumer interest in the costs, benefits, risks, and performance of hydrogen technologies [178]. Whether knowledge is 'perceived' (i.e. subjective) or 'actual' (i.e. objective), it typically enables consumers to feel more confident about making informed decisions [68]; acting as a driver for decision-making and leading to support if aligned to the positive aspects of hydrogen technologies such as their potential environmental benefits [87].

Several survey studies have highlighted the impact of information framing on hydrogen acceptance. Molin [228] found that 'colored' information (i.e. positive, negative and neutral framings) had a direct impact on hydrogen perceptions, influencing consumer attitudes and willingness towards using hydrogen in the Netherlands. In Australia, environmental messaging about hydrogen[8] had a small but statistically significant effect on support levels; compared to alternative messages about the following: the role of hydrogen blending in the energy transition; the economic benefits of the national hydrogen economy; or policy solutions to make hydrogen energy more affordable for households [86]. In contrast, Damette et al. [70] found that presenting French participants with alternative framings regarding hydrogen's benefits (to the grid, household, or environment) had minimal impact on willingness to choose a hydrogen-based storage system over their current system. However, the study did report novel findings in that participants preferred a different kind of energy system management according to the information framing. Specifically, those informed about environmental benefits were more in favor of the hydrogen system being managed by an energy cooperative, while those aware of household benefits preferred a public management system.

Increased knowledge may result in finer attunement to both the positive and negative aspects of hydrogen applications [83]. When viewed as an environmentally friendly fuel that is suitable for commercial applications [94,228], positive perceptions tend to prevail over safety concerns around hydrogen's explosivity [60,83,228]. Overall, informing the public about hydrogen's historical significance, regulatory status, technical development, and environmental credentials seems to contribute to more positive perceptions (see Table 5), especially when there is a desire to know more about the technology [68].

[7] Manufacturers note that flame visibility is not strictly necessary for heating and hot water appliances due to the sealed combustion chamber and presence of remote flame indication on most boilers, but largely support the requirement for it [67].

[8] "Australia can use its abundant renewable energy resources to produce hydrogen, which will give us 100% emissions-free 'green' energy."

Table 5
This table reports the impacts of information provision on domestic hydrogen acceptance. The results suggest that positive perceptions of hydrogen are more likely following information provision.

Study	Details of information provision	Results on public perceptions
[42, 75, 87]	• Following the 1990 (2009/142/EC) Gas Appliance Directive (GAD), all appliances manufactured and/or sold in the UK (and EU) since 1993 have been subject to and must pass a short-term test to run on a maximum of 23% hydrogen [42, 75,87] • Prior to natural gas, most UK homes and businesses ran a manufactured mixture called 'town gas'; composed of a mix of methane (CH_4), carbon monoxide (CO) and up to 50% hydrogen [42,75,87] • The development of R&D activities [42]	• Greater willingness to participate in community trials for blended hydrogen [42] • Support for hydrogen as a fuel for participants' local areas, for a trial taking place within these areas and for hydrogen as a national fuel scored 6.81, 7.08 and 6.89 out of 10 [87] • Less than 10% of survey participants placed 'no value' on hydrogen [75]
[68]	• A video excerpt of the Leeds City Gate H21 City Gate Project	• Stronger support for domestic hydrogen after viewing the video
[69]	• A new type of domestic gas supply is coming which is unrelated to fracking • This gas will be better for the environment as it has a low carbon footprint • Should the change go ahead, it will apply nationwide regardless of existing energy suppliers • The government will arrive at their decisions within the next 5–10 years	• Respondents previously 'cautious', 'disinterested' or 'unconvinced' about the conversion of natural gas networks and use of hydrogen in their homes were more likely to become 'accepters' of a potential conversion; viewing hydrogen "as an option that needs serious consideration." • Respondents were able to understand and relay basic technical details about the hydrogen conversion in a clear and simple way
[70]	• All participants were provided the same information on hydrogen energy storage, explaining in layman terms why the technology is useful as part of the energy transition and how it can be used in the home	• Participants proved more willing to choose hydrogen-based energy storage systems over the current energy system • Strong positive correlation regarding energy self-sufficiency and support for the proposed hydrogen storage system
[86]	• A video excerpt explaining what hydrogen energy can be used for, how 'green' hydrogen can be produced, and the potential for export markets[a] • Further images and text further explaining a range of hydrogen production methods • Information on how domestic use of hydrogen can reduce emissions, and that trials with up to 20% hydrogen blends have already been trialed in Europe	• Stronger support for domestic hydrogen following information provision • Overall, respondents were slightly to moderately willing to use hydrogen for all domestic purposes (hot water heating, cooking, on-site electricity generation, space heating, blended hydrogen, and HFCVS), with stronger support for hot water heating and cooking
[88]	• A video excerpt on Australia's hydrogen opportunity[b]	• Many participants expressed positive sentiments and agreed that developing a hydrogen industry in Australia seemed like a good idea that could bring economic, energy security, and environmental benefits • Questions were raised about safety, potential costs, local employment opportunities, water scarcity and environmental trade-offs
[89]	• Neutral general information about hydrogen energy technologies, in addition to specific information about the	• Participants considered themselves more likely to accept and support the adoption of

(continued on next page)

Table 5 (*continued*)

Study	Details of information provision	Results on public perceptions
	consequences of residential fuel cells and HFCVs	residential fuel cells (and HFCVs) all other things being equal
[233]	• Learning assignments in Aalto University, School of Engineering, related to hydrogen safety and small-scale hydrogen production	• Finnish engineering students were more willing to acquire a small-scale domestic hydrogen system once better informed about hydrogen safety

[a] https://www.youtube.com/watch?v=fFGT2z82tOM.
[b] https://www.youtube.com/watch?v=nO63TyoTNxE.

Bogel et al. [76] made an explicit contribution to bridging the knowledge gap on the attitudinal dimensions of hydrogen acceptance, through an assessment of prior perceptions about hydrogen and emergent attitudes following information provision. The study argued that information campaigns based on short and somewhat neutral information may prove a powerful tool at the early stage of technology diffusion, especially when aimed at parts of society with minimal knowledge about hydrogen. By contrast, research on the Polish electromobility market flagged that only 22% of respondents (N = 171) believed that such campaigns would have a positive influence on market deployment and social acceptance of HFCVs, whereas cost reductions and infrastructure development were supported by 90%. Furthermore, Williams et al. [121] found that less than half of respondents felt they understood significantly more about hydrogen boilers or heat pumps after being provided with additional technical information. Martin et al. [86] have also cautioned that factual information may not necessarily increase support levels when strong opposition to hydrogen is preexisting. Notwithstanding, information provision may prove effective when initial attitudes are neutral, or support already exists [76]. Moreover, public engagement with and exposure to HETs may facilitate opportunities for successful market adoption, while also increasing consumer willingness to pay [229] (see Table 6).

4.1.5. Socio-structural factors and hydrogen acceptance

Following Schönauer and Glanz [103], socio-structural factors may prove important to the evolution of hydrogen acceptance. A positive correlation between knowledge and acceptance of hydrogen technologies is noted in the literature [12,227], which typically depends on factors such as higher levels of education, environmental awareness, technology engagement [174], income [99,230], and full-time employment [231]. Notably, Iribarren et al. [94] reported largely positive perceptions of hydrogen's environmental credentials and suitability for Spanish public transportation. The survey study reflected the potential importance of socio-demographic variables to technology acceptance [232], since 72% of respondents were younger than 35 years old and 61% had at least university level education. By contrast, younger Germans were more likely to oppose hydrogen infrastructure on Not-In-My-Back-Yard (NIMBY) grounds, while eldest respondents were the most supportive demographic [103].

Other evidence suggests that older age groups could be somewhat less accepting of HET [12], indicating that the effect of certain socio-demographic factors may prove to be highly place- and context-specific. Researchers in South Korea [99] found that education and income had a positive effect on hydrogen acceptance, while household characteristics also had a significant effect. Irrespective of age, gender, or cultural worldviews,[9] people with limited technical or scientific knowledge may prove less likely to support hydrogen technologies [171]. Tellingly, Bellaby and Upham [231] noted that UK motorists knew more about hydrogen than non-drivers and were more supportive.

In some cases, socio-structural factors may have a weaker influence on acceptance compared to psychological factors [12], especially risk perceptions factors [108]. Notably, Scott and Powells [87] found the relationship between support for hydrogen blending and socio-demographic variables such as age, sex, education, and income to be statistically insignificant. While this finding should not be dismissed outright, it contradicts the wider literature and is yet to be verified in follow-up studies (see Table 7). One explanation could lie with the location of UK survey participants not being verified as part of the study design, while the researchers only screened for a limited selection of socio-demographic characteristics. Additionally, a larger sample size (>N = 742) would provide more reliable data on the statistical significance of socio-demographic variables. In response, a new wave of quantitative research is needed to examine the impact of both information provision and socio-structural variables on domestic hydrogen acceptance.

4.2. Barriers to socio-political acceptance

4.2.1. Consumer engagement and trust in the energy transition

Consumer engagement and socio-structural factors may influence

Table 6
Impacts of public engagement and experience on hydrogen perceptions.

Study	Country	Findings
[100]	Japan	• Familiarity with hydrogen refueling increased acceptance for drivers
[116]	USA	• Experience with HFCVs and refueling stations was mostly positive for a volunteer group of Californian drivers • Responses largely exceeded initial expectations when considering the performance, safety, and practical aspects (N = 54)
[117]	Netherlands	• People living in proximity to a hydrogen fueling station (HFS) were more accepting of this technology following its implementation • Respondents attributed more weight to benefits and less weight to risks than beforehand
[127]	UK	• Following participation in the Hydrogen Bike activity,[a] 88% of respondents previously neutral or with no opinion on hydrogen, now reported a positive feeling

[a] A public exhibit set up to engage participants with a hydrogen bike demonstration and scientific information about hydrogen.

Table 7
This table reports the impact of socio-demographic variables on hydrogen acceptance. The results suggest that age, gender, and education may influence consumer attitudes towards hydrogen, especially regarding safety perceptions.

Study	Findings
[89]	• Male respondents reported a higher level of acceptance relative to female • Those in younger age groups reported a higher level of acceptance
[68]	• Australian women had stronger reservations about the potential disruptive impacts of hydrogen in view of its physical and chemical characteristics, including stronger concerns about hydrogen's odorless nature. • Highly educated respondents were more supportive of using hydrogen for all domestic purposes (i.e. space heating, hot water heating and cooking). • 65% of male respondents either 'very supportive' or 'supportive' of domestic hydrogen, compared to 40% of female respondents.
[83]	• Young, educated males had the most knowledge about hydrogen • Males perceived hydrogen as more explosive and dangerous than females • Older age groups had the strongest perception of hydrogen as unsafe.
[80,174, 234]	• Men are more likely to have prior knowledge about hydrogen, making them more inclined to have positive perceptions.

[9] These include trust in technology and environmental awareness, and to a lesser degree (Christian) stewardship for nature and spiritual holism [171].

how the public perceives the costs, benefits, and risks of technology adoption [235], and whether they trust in institutions, actors, and information. At present, widespread consumer disengagement in the energy market remains an obstacle to net zero ambitions and climate change targets (see Table 8). Notably, the UK public remains largely disengaged with developments in the energy market, with around a quarter of consumers yet to switch energy supplier once [181]. According to Ofgem, 54% of consumers remain on expensive default standard variable tariffs (SVTs) [236],[10] while those that switch typically stay the same supplier [237] Citizens most likely to have switched included homeowners and those aged 65 and over [181].

Based on Eurobarometer survey data, Balta-Ozkan and Le Gallo [238] indicated that socio-structural factors may shape trust in institutions, actors, and information. Specifically, gender, income, location, and housing tenure acted as potential determinants of renewable energy acceptance. More years in education, home ownership, and being female contributed positively towards trust in energy companies, whereas energy saving practices and internet access undermined trust levels. Owning a computer and having access to the internet resulted in negative perceptions of fossil fuels and more distrust in utilities as a provider of information, compared to more positive perceptions of RESs and stronger trust in the scientific community, not-for-profit organizations, and the EU. Additionally, homeowners, who have paid or still paying off their mortgages, were also more likely to trust in supra-national, national, and sub-national government [238].

Table 8
This table summarizes findings on public perceptions of the energy sector and energy transition. The results show that greater levels of public trust are needed to support the transition.

Study	Findings
[69]	• Limited engagement with the energy sector beyond switching energy supplier
[70]	• Consumers expressed weak preferences for hydrogen homes to be managed by private companies, placing more trust in energy cooperatives and municipalities
[122]	• Mistrust over the issue of 'green taxes', which some see as a political ploy to extract more tax revenues without a real commitment to addressing environmental problems
[144]	• In terms of financing the UK energy transition, respondents assigned most responsibility to energy companies (45%), followed by government (32%), the public (12%), and future residents (11%)
[239]	• Deep rooted public mistrust of electricity companies • Trustworthiness and popularity of community energy schemes
[238]	• Residents in large urban areas[a] had greater trust in government and political entities than rural residents • Both large and small city residents were more trusting in the EU, scientists, environmental protection agencies, and journalists than their rural counterparts
[240]	• Consumers regard the transactions of energy companies as opaque, leading to distrust and suspicion, especially when prices rise despite technological advancements
[241]	• Mistrust is more common in communities disengaged from actively managing their energy choices and consumption costs
[242]	• The credibility of promoted energy savings schemes is undermined when consumers perceive power companies as deriving profits from increased energy consumption
[243]	• The public considers energy companies as accountable for helping to lead the transition, but view their contribution to date as insufficient, especially given their ability to invest sizeable capital in low-carbon energy infrastructure and technologies Conditions for establishing public trust are especially challenging when energy companies are primarily perceived as "profit-making entities"

[a] The terms large cities, large urban areas, and large urban communities were used interchangeably.

4.2.2. Public trust in the hydrogen transition

Early hydrogen acceptance studies conducted in the UK [79,81,172] suggested mixed reports concerning public trust levels in institutions, actors, and information, as well as perceptions of safety issues, risk management, and trust. Based on findings from the final survey phase of the BP-Imperial College (BP-IC) Hydrogen acceptance project (2004–2007), O'Garra [172] reported a wide discrepancy between consumer trust levels according to the information provider. It was noted that perceptions remained fixed throughout the study period, indicating that trust may be hard fought and somewhat static.

More recently, in the context of the HyDeploy demonstration project,[11] the underlying motives of the central government were viewed with skepticism [87]. Due to past policy failures and inconsistent messages regarding energy technologies such as the promotion of diesel cars and solar panels [122], the UK public may see the central government as a credible authority in some respects, but also feel distrust and suspicion [42]. This is reflected by a perceived lack of trust in key decisions makers and the overall system of governance, which may stifle stakeholder inclusion and participatory processes at the community level [123]. The credibility of the UK government may be further undermined due to failure to lead by example on the part of elected officials [42].

Overall, the evidence base underscores an apparent rift between public perceptions of intentions and actions regarding the government, industry, and business (see Table 9). The public appears willing to trust the government and gas companies to manage safety challenges and risk factors, while remaining skeptical about the commitment of these entities to procedural justice.

Trust levels and related attitudes towards key actors may also vary significantly between communities and according to socio-structural factors. For example, younger demographics in Australia were less willing to trust the government and expressed a preference for community-based projects, while older participants flagged their concerns over how urban areas have been given preferential treatment at the expense of regional communities [88]. Elsewhere, the DGA [122] reported a divergence between respondents in the North and South of England, especially regarding safety perceptions, which appears to reflect a wider rift in terms of socio-political acceptance. Southerners were more cynical about the motives of businesses and skeptical about hydrogen delivering energy efficiency improvements to industry or business, whereas northerners were enthusiastic about these prospects, which could be attributed to a greater sense of pro-hydrogen 'place attachment' [244] and 'place-technology fit' [137] linked to the north's industrial heritage.[12]

4.2.3. Hydrogen production pathways

At present, around 95% of global hydrogen production is sourced from fossil fuels, which includes 48% via steam methane reformation (SMR), 30% from petroleum fraction, and 18% from coal gasification [245]. SMR is dependent on large quantities of natural gas [246], making it environmentally contentious [247] and highly cost-intensive [248]; nevertheless, it remains the most technically feasible and economical method for delivering large-scale hydrogen production [246,247,249]. Electrolysis – the process of electrochemically converting water into hydrogen and oxygen using renewable electrical energy [250] – accounts for around 4% of global hydrogen production [245]. Electrolysis is increasingly considered as an alternative pathway to achieving large-scale hydrogen production with a lower carbon

[10] The difference between the average SVT price of the six large suppliers and the cheapest market tariff was on average £320 between June 2017 and June 2018 [236].

[11] Launched on Keele University's private gas network to test the safety case for hydrogen blending.

[12] A locality characterized by a history of socio-economic deprivation and unemployment, as well as a legacy of pollution and environmental degradation due to the presence of heavy industry.

Table 9
This table summarizes findings on public trust in the hydrogen transition. The results show the extent to which trust levels may vary according to actor or stakeholder.

Study	Country	Findings
[68]	Australia	• High trust in government, moderate trust in research organizations, and low levels of trust in the media to disseminate information
[68,86]	Australia	• Research institutions as the most trustworthy entity for acting in the public's interest, followed by environmental non-government organizations (ENGOs)
[68,86, 87]	UK, Australia	• Skepticism about the motives of fuel/gas and electricity generation companies
[68,87, 123]	UK, Australia	• Strong public trust in gas companies and the government to uphold stringent safety standards for hydrogen gas and manage environmental risks competently
[79]	UK	• Opposition to hydrogen storage and refueling facilities in London was strongly associated with inadequate trust in safety regulations, as well as non-environmental attitudes
[87]	UK	• Local Members of Parliament (MPs), and the media considered as untrustworthy sources of information concerning hydrogen • Public trust was highest in evidence provided by the Health and Safety Executive (HSE), followed by universities
[179]	UK	• Low risks levels associated with hydrogen technologies due to underlying trust in safety processes and measures.
[172]	UK	• Stronger trust in information sourced from universities, the BBC, and environmental organizations • Oil companies and car companies considered the least trustworthy
[103]	Germany	• Higher trust in scientific stakeholders resulted in less NIMBY opposition to hydrogen infrastructure • Higher trust in civic stakeholders increased NIMBY opposition Trust in political stakeholders led to more community acceptance but also more ambivalence
[117]	Netherlands	• Trust in industry had a positive effect on feelings of pride and joy, and a corresponding negative effect on fear for citizens living in proximity to a HFS
[122]	UK	• Neutral trust in regulators such as the Office of gas and electricity markets (Ofgem)
[123]	UK	• Uncertainty about whether the national government, local councils, and local businesses can be trusted to make good decisions about hydrogen technologies

footprint [251].

The legitimacy of this alternative is well reflected by a divergence in the recent literature on 'socio-technical-economic' aspects of hydrogen production and deployment [252]. Studies published between 2008 and 2012 concluded that SMR-based hydrogen production would be the lowest-cost method over the long-term, whereas subsequent studies (2013–2017) contend that electrolytic hydrogen can become cost competitive [252]. This argument follows the higher penetration of RESs into the electricity grid [252], and the prospect of further declining costs for renewables [253] including wind and solar power [54]. Furthermore, there is significant potential to scale up renewable hydrogen sourced from curtailed electricity [254–256]. Given hydrogen's advantage as a power storage medium, this could enable more efficient electricity grid management [255,257]. Considering the high capital loss of wind energy, converting curtailed energy into hydrogen may prove more economical than extending the UK electricity network [258]. Consequently, offshore wind farms (OWFs) may present the best investment opportunity for achieving a hybrid energy system using Power-to-Gas (PtG) sourced from electrolytic hydrogen [259].

In effect, the global hydrogen landscape is evolving to include a range of industrial, commercial, and domestic applications centered on a combination of large volumes of carbon capture, utilization and storage (CCUS-) enabled ('blue') and electrolytic ('green') hydrogen [260]. Since green hydrogen faces a scarcity challenge in the near-to medium-term which may prevent economies of scale, blue hydrogen could play an enabling role in supporting "the uptake of hydrogen infrastructure and hydrogen end-use transformation" [261].

As envisioned in the UK Hydrogen Strategy, this 'twin track' approach is designed to help 'future-proof' the country's net zero ambitions by avoiding over reliance on a single technology pathway [18]. The strategy builds off the target for 5 GW of low-carbon hydrogen production capacity economy-wide by 2030, as set out in the Ten Point Plan for a Green Industrial Revolution [262].[13] The evolution of mixed production pathways for hydrogen over the short-, medium- and long-term is further reflected in Points 1 and 8 of the UK government's Ten Point Plan, aiming to achieve a four-fold increase in offshore wind capacity by 2030, and capture of 10 Mt of carbon dioxide (CO_2) by 2030 through the £1 billion CCUS Infrastructure [262].

4.2.4. *Environmental impacts*

Hydrogen's environmental impacts are a matter of growing controversy in the scientific community [263]. Although hydrogen is by most measures a clean energy vector with a critical role to play in decarbonization, its potential adverse climate change and environmental impacts remain underexplored by atmospheric scientists and the wider scientific community [264]. The climate change credentials of blue hydrogen rest on at least two key parameters linked to greenhouse gas (GHG) emissions. Firstly, the global warming potential (GWP) of CH_4 is around 25–28 times higher than that of CO_2 over a 100-year time horizon [265], signaling the importance of upstream CH_4 emissions for a net zero transition [261]. Secondly, and equally applicable for green hydrogen, the GWP of nitrous oxide (N_2O) is around 300 times that of CO_2 [266]. Discussing the downstream consequences of hydrogen boilers, Lewis [267,268] has further warned that potential NO_X emissions from hydrogen boilers may fall disproportionately among disadvantaged communities and low-income households. In the UK, this point is especially pertinent given that domestic hydrogen transition will begin with industrial towns in the North of England [154,269].

The climate change impacts of hydrogen have also been examined from a life cycle assessment (LCA) perspective [261,270,271]. If blue hydrogen production is to prove compatible with climate change mitigation, CH_4 emissions rates of the natural gas supply chain must be kept below 0.5% and combined with higher CO_2 capture rates above 95% [261].[14] In the case of green hydrogen, the carbon intensity of the electricity grid should be below 70 kgCO2,eq/MWh to be comparable to the best blue hydrogen production practices [272]. Other environmental impacts include particulate matter formation, terrestrial acidification, mineral resource depletion, and freshwater ecotoxicity [272].

4.2.5. *Public perceptions of hydrogen production and environmental impacts*

Hydrogen can be produced by various means [18], however, evidence on public perceptions of production pathways remains largely limited to highly developed economies, with an underlying focus on blue and/or green production (see Table 10). In the case of hydrogen produced via nuclear power, social acceptance issues may persist due to negative safety perceptions in the public sphere [39]. Even for a leading nuclear power producer such as South Korea, public perceptions may be highly polarized [230].

Despite the controversy surrounding the idea of blue hydrogen as a bridging technology to renewable-based production methods [261,273], few studies have examined whether the public may tolerate the idea of

[13] Estimated to be equivalent to the amount of gas consumed by over 3 million households each year.

[14] Exhibiting a life cycle GHG footprint of not more than 2–3.5 kg CO_2- eq./kg [261].

Table 10
This table reports on public perceptions of hydrogen production methods and environmental impacts. Results indicate stronger support for hydrogen produced from renewable energy sources.

Source	Findings
[50]	• In Pakistan, biomass and solar energy ranked as more acceptable sources of hydrogen production than wind, municipal solid waste (MSW), and geothermal
[42,121]	• Dual-fuel appliances may require natural gas to act as a backup power source could prove contentious due to environmental impacts
[68,86,88]	• Strong support in Australia for hydrogen's promise as a potential solution for environmental and energy challenges
[75]	• 70% of UK respondents believed hydrogen fuel would have positive impacts on the environment
[76]	• Most EU citizens considered hydrogen to be a good or very good solution for energy and environmental challenges • Agreement levels increased from 75% to 84%–92% according to level of familiarity with the technology (*slightly familiar, familiar, very familiar*)
[86,128,129]	• Respondents in Australia, Germany, and the Republic of Ireland perceived water scarcity as a risk factor for electrolysis-based hydrogen
[88]	• 74% of Australian respondents were in favor of renewable-based hydrogen production and believed it would help protect the environment • Only 24% backed CCS as a long-term option while 54% accepted blue hydrogen as a transitional fuel
[123]	• UK respondents preferred green and blue hydrogen to natural gas, with mean scores of 82/100 and 59/100 • Natural gas was somewhat preferred to brown hydrogen, scoring 32/100
[128]	• All participants in the Republic of Ireland preferred green hydrogen, with limited tolerance for other production methods.
[230]	• 40% of South Koreans accepted hydrogen produced from nuclear power, 40% were neutral, and 20% were in opposition
[231]	• Stronger public support for renewable-based hydrogen generation than fossil-fuel or nuclear-based production methods. However, CCS did not feature as a technology option in this UK opinion poll
[275]	• Social awareness of wind energy in Iran is associated with higher acceptance of wind turbines as a hydrogen generating source

an enabling role for SMR and CCS in the hydrogen transition [274]. When considering Australia's energy future, the public expressed similar, albeit slightly lower support levels for hydrogen compared to wind and solar power, which eclipsed support for nuclear power or fossil fuels [86]. Interestingly, there was stronger belief that hydrogen should be sourced solely from renewables [86] compared to previous studies [68,88]. Non-renewable based production methods may present a barrier to acceptance, especially among more environmentally conscious parts of the public [68,231]. Notwithstanding, the public appears to recognize that the timeframes for producing renewable hydrogen at scale remain uncertain [69].

For the most past, social acceptance has been gauged through results from public surveys and focus groups. Some researchers have employed alternative methods such as structural equation modeling (SEM) [275], or a two-stage fuzzy multi-criteria decision-making (MCDM) approach [50]. However, studies relying strictly on computational methods may lack validity when it comes to assessing social acceptance at a community or individual level.

Acknowledging the contested policy space surrounding hydrogen and electrification [123], Damette et al. [70] provided a more nuanced analysis of public perceptions of decarbonization pathways regarding hydrogen homes. The study analyzed three scenarios in the French context: (1) hydrogen is converted into electricity off-site and then supplied to households using existing electricity transmission networks (power-to-gas-to-power); (2) hydrogen gas blended with natural gas (PtG) is supplied and used as a fuel in boilers to create heat; (3) hydrogen gas is supplied directly to the residence and can be transformed into heat and electricity by a co-generation boiler. A principal finding was that consumer preferences may depend on familiarity levels with different energy carriers. Overall, consumers preferred the first option compared to the gas-based alternatives, which was especially true for households relying solely on electricity. Furthermore, French gas users proved largely indifferent to these supply methods, which contradicts evidence in the UK [123]. A possible explanation could lie with distinct energy cultures, namely a well-established gas culture in the UK [276], compared to a high penetration of nuclear power in French electricity generation [277].

4.3. Barriers to market acceptance

4.3.1. Economic factors through the UK lens

The net economic impacts of hydrogen are strongly influenced by its cost-competitiveness [18]. For blue hydrogen, this will depend on how the price of hydrogen compares to natural gas [68], among other factors such as CH_4 leakage rates and the costs of CO_2 storage [261]. More broadly, the energy trilemma – defined by problems arising from economic (energy finance), politics (energy security), and the environment (climate change mitigation) [278] – presents a growing problem to countries such as the UK [279]. These factors strongly impact public perceptions of energy policy and emerging technologies such as hydrogen. Notably, in response to recent market volatility[15] – arising from growing geopolitical tensions, economic instability, and a series of unfavorable local and global weather patterns [280], which met the worst of conceivable risk scenarios [281] – Ofgem increased the energy price cap by £139 to £1,277 [282]. Following October 1, 2021, this change directly impacted approximately 15 million people nationwide [283].[16]

The public faces a time of growing uncertainty when it comes to energy costs, which raises consumer expectations for reduced energy bills once natural gas is replaced by low-carbon energy sources. However, consumer research led by the UK's largest Gas Distribution Network Operator (GDNO), Cadent Gas, suggests that most households incorrectly associate a switch to a low-carbon hot water and heating solution with lower long-term running costs [284].[17] In addition to cost-competitiveness and security of supply factors [280,285,286], market acceptance will depend on how socio-economic benefits are delivered through regional development and employment opportunities, as part of the UK's industrial strategy [287,288]. Notably, there is significant potential for industrial symbiosis and hydrogen hubs, which could bring regional economic benefits [123]. In this respect, lessons can be learned from the missed opportunity of developing local supply chains around the offshore wind industry [123,289].

4.3.2. Public perceptions of economic impacts

Evidence suggests that the UK public may regard the impact of domestic hydrogen on the national economy to be either neutral or positive [75]. One study found that approximately three-quarters of online survey respondents perceived that there would be 'no impact' on the economy, while nearly one-quarter saw a potential 'positive impact' [75]. For respondents who took the paper survey, there was an approximate 60-40 split between neutral and positive perceptions. In contrast, the Australian public had mostly positive perceptions about the hydrogen transition creating new jobs and opportunities for skills acquisition [68]. This discrepancy between national contexts could be because the ARENA study examined perceptions and attitudes towards

[15] The UK natural gas price peaked at around 290 pence per therm in October 2021, compared to an annual low of 36 pence per therm in March [325].

[16] Ofgem reviews and sets the energy price cap twice a year to limit how much suppliers can charge domestic customers for gas and electricity, applying to customers on default (SVTs) tariffs [282,283].

[17] This finding was reported in Cadent's Triangulation report – *Developing a Greenprint for Gas: Customer Preference Research* – which is due for publication in 2022 as a follow up to Ref. [284].

hydrogen in the transport sector, for domestic use and moreover, as an export commodity [68], whereas Scott and Powells [75] looked solely at hydrogen as a fuel for UK homes.

Importantly, consumers want to see community benefits prioritized, whereby the economic benefits of new jobs can support future generations [88]. This especially means safeguarding against the risk of a 'boom and bust' cycle around emergent hydrogen hubs [88]. In response, researchers should target a deeper understanding of how the public perceives the prospect of socio-economic benefits being delivered through projects such as HyNet North West, which exemplifies the drive to develop regional hydrogen hubs in proximity to industrial clusters [290]. Interestingly, existing industrial structure may also increase consumer acceptance towards hydrogen technologies, specifically HFCVs [114]. Data collected in China (Jiangsu Province) suggested that cooperation between industries and manufacturers promotes public trust in industrial agglomeration around the hydrogen economy [114].

To date, few studies have compared consumer preferences for hydrogen applications, while limited public feedback is available on national hydrogen strategies. In Germany, 65% of survey respondents ($N = 512$) rated the use of hydrogen as an energy carrier (e.g. for heat, in transport, or in industry) as 'very positive' or 'positive' [103]. Interestingly, consumer acceptance in Leeds proved highest for public transport applications, based on a mean score of 80/100, compared to 75 for vehicles, 71 for refueling stations, and 69 for heating [123]. However, these results predate the publication of national hydrogen strategies. Follow-up studies are needed to better gauge how social acceptance for domestic hydrogen may interact with, or even depend on, public response to other hydrogen applications.

4.3.3. Technology choice

By choosing between hydrogen boilers and other low-carbon heating solutions [138], which implies supporting different production pathways, households will play a key role in determining the evolution of national gas infrastructure networks and electricity grids [68]. As discussed in section 4.1.1, hydrogen acceptance is likely to hinge on how its technical complexity and unfamiliarity compare to other low-carbon technologies for domestic heating and cooking [121]. Additionally, technology choice could determine the public's willingness to adopt hydrogen energy technologies [89], which may depend on perceptions of substitutability [138]. Substitutability has proven to be a prerequisite for securing social acceptance in the case of electricity sources such as nuclear power [291,292] and may prove equally critical to how the public chooses between hydrogen appliances and competing technologies [138].

Compared to alternatives such as heat pumps and district heating [138], the public seems to perceive hydrogen as more of a direct substitute for natural gas, since it would be supplied to households in a similar way following structural changes to the national gas grid [121]. In terms of technology preference, the DGA [122] found that support levels were highest for blending hydrogen and biomethane into the grid, followed by converting home heating to hydrogen. A hybrid heating system – combining an electric heat pump and an existing gas boiler – also proved more popular than heat pumps.

The UK public appear to view heat pumps as a subpar substitute for natural gas boilers due to greater spatial requirements, and potentially disruptive and inconvenient performance characteristics [122]. However, following information provision, Williams et al. [121] reported that 45–55% of respondents had no clear preference towards either hydrogen heating or heat pumps. This observation raises further questions about the public's technical understanding of low-carbon heating solutions. Nevertheless, should the hydrogen economy succeed in increasing overall market choice for low-carbon energy technologies, consumers may prove more in favor of the transition [115].

Decisions to adopt hydrogen home appliances may also depend on customer loyalty to their current boiler manufacturer. This factor could become highly influential, given that market leaders Worcester Bosch and Baxi Heating are key actors in the UK's hydrogen trials [293,327]; having developed prototype hydrogen boilers for the Hy4Heat programme [19]. Two of the other 'big four' boiler manufacturers have also committed to selling a new generation of 'hydrogen-ready' boilers at a similar point to natural gas systems on a volume basis [294,295].

Lambert and Ashworth [68] obeserved that younger and higher educated Australians expressed more support for electrification. All-electric households were less supportive of the use of any hydrogen in the gas network, whereas support for hydrogen was higher in urban areas and locations with frequent power outages. It should also be noted that households relying on or intending to use electric cookers or heat pumps may prefer to have no connection to the gas grid [121]. Regarding gas preferences, Ashworth et al. [88] found that 67% of participants preferred hydrogen, while 26% were undecided and only 7% chose to remain with natural gas. Based on this finding, there may be a prevailing tendency for consumers to support hydrogen when choosing strictly between gas-based heating and cooking, as opposed to electric or other alternatives.

First steps have been taken to gauge the public's perceptions of hydrogen appliances, including those running on a blend of up to 20% hydrogen, compared to other low-carbon alternatives such as heat pumps. Overall, the public appears receptive to the idea of hydrogen blending as a non-disruptive or potentially positive technology, suited to preserving the lived experience of heating and cooking with natural gas [75]. However, there is sparse evidence on public perceptions of a full-scale conversion to domestic hydrogen use, as opposed to hydrogen blending which has been promoted as a practical, safe, and viable interim decarbonization pathway [60]. More research is needed to determine if a full-scale conversion to hydrogen homes will be viewed comparably, while understanding the reasons why the public may hold certain views towards alternative technology options for domestic heating and cooking. Given the dynamic and hybrid nature of the low-carbon transition, researchers should aim to understand whether these options are seen as competing or complementary decarbonization pathways in the eyes of the public.

4.3.4. Boiler replacement trends and socio-economic factors

Reviewing the uptake of seven energy efficient heating systems, Ipsos MORI and the Energy Saving Trust [296] found that 30% of respondents cited system breakdown as the main reason for replacing their heating system, while 36% had never done so and 19% anticipated waiting more than 20 years to do so. These results reflect the fact that 1.67 million gas boilers were sold in the UK in 2019 [297], representing around 7% of homes connected to the gas grid [298].[18] Importantly, system breakdown is the most common trigger for homeowners to consider replacing their heating system [296]. However, a large proportion of the UK housing stock has never undertaken such a replacement and moreover, expects this to happen around once every fifteen years [296].

Assuming that the average life of a boiler is approximately 12 years, a high percentage of households may be several years away from changing their boiler unless there is a direct incentive in place [67]. Consequently, consumers will be more hesitant to make a system change having recently bought a new boiler, especially when this includes an upfront service plan [42]. Consumers could therefore reject the switchover if worries over financial losses amount to a feeling of technology lock in, following a recent purchase or modification [42]. Overall, consumers appear more willing to adopt low-carbon heating systems when their existing gas boiler needs replacement, with cost being the key factor behind this decision [121,296,299].

People with low incomes or savings are less likely to have previously replaced their heating system and expect to do so with less frequency

[18] It is estimated that the number of UK homes with a gas connection increased from around 7.7 million in 1970 to around 23.3 million in 2011 [326].

than higher-income earners [296]. Additionally, low-income groups are less likely to install a more efficient heating system than higher-income groups [296]. These findings are unsurprising since inability to afford new technologies falls disproportionately upon low-income earners [300,301], making fuel cost a more significant factor to this demographic group [68]. Dorrington et al. [67] highlight further reluctance on the part of consumers, given that appliances rolled-out during the early stages of the transition may have relatively shorter lifespans than current natural gas appliances or future hydrogen appliances. Notably, hydrogen's flame characteristics may decrease the lifetime durability of appliances, calling for more frequent and modified maintenance measures, which may dissuade consumers if there is a perceived lack of trained engineers and skilled technicians [42].

4.3.5. Hydrogen cost factors

At the micro-scale, market acceptance is shaped by the extent to which consumers are forced to absorb costs of the hydrogen transition, largely stemming from high production costs [248]. This could materialize through higher taxes and/or energy bills levied nationwide, in addition to purchases made for new appliances or smaller payments to modify existing natural gas appliances [72,75]. Burke and Rooney [302] estimate the total costs of converting gas appliances to hydrogen to be around £3,000 per home, which is still much less capital-intensive than most alternative low-carbon technologies such as heat pumps. While annual running costs vary marginally, the total installation costs of air source heat pumps (ASHPs) have been estimated to range between £5–10 k [302], £5–8 k [303], or £7–13 k [304], while ground source heat pumps (GSHPs) range between £10–15 k [302], £11–15 k, or £14–19 k [304], according to house size and area [303].

The UK Government recently announced a £450 million Boiler Upgrade Scheme to support households with grants of £5,000 or £6,000 when making the switch to an ASHP or GSHP [19]. However, this level of funding amounts to a potential switchover for approximately 30,000 homes over a three-year period, which pales in comparison to the current target for 600,000 heat pump installations per year by 2028, as part of the *Greener buildings* objective [262].[19] Consequently, hydrogen boilers would present a more attractive purchasing option for low-income households, as well as other consumers unable to invest in high up-front costs. Furthermore, it is anticipated that the market price of hydrogen boilers could be equivalent to natural gas boilers by 2030 [305].

4.3.6. Public perceptions of financial costs

In the context of a hydrogen heating community trial, Grey et al. [42] identified a range of potential barriers to market acceptance for potential early adopters, such as costs and disruptive impacts, which can be extrapolated to the switchover and wider transition. The study reported that UK consumers want to feel confident about the stated or promised savings being fulfilled, placing high importance on investment, operational and lifetime costs, energy prices and tariff structure. Consumers are especially concerned about purchase costs since a switchover to domestic hydrogen is likely to require personal (financial) investments in new appliances [68,87], which the public expect to be subsidized [123]. Such expectations are mirrored internationally, with 95% of Taiwanese respondents calling a government subsidy of at least 22% to support the purchase of hydrogen-electric motorcycles [304]. Similarly, most Polish users of hybrid and electric vehicles (91%; N = 171) regarded financial and fiscal incentives as having the most positive impact on willingness to purchase HFCVs.

UK respondents view low energy bills, and purchase and running costs, as the most important factors of new heating systems, attributing less importance to functionality, efficiency, reliability, or aesthetics: 24% and 23% of respondents cited low energy bills and low running costs as the most important criteria; 10% regarded capital costs as an important factor; and 5% prioritized cheap purchase and installation [296]. As has been the case for renewable electricity [140], it is apparent that willingness to pay for low-carbon technologies such as hydrogen will depend on socio-structural factors [306]. According to Wave 37 of the Department for Business, Energy & Industrial Strategy (BEIS) public attitude tracker (March 2021), 29% and 11% of the public were 'fairly worried' and 'very worried' about paying for energy bills, which marked a 3% increase from the previous year [181]. The most worried demographic group were those aged 25 to 34 in social grades C2DE, while private and social renters expressed higher concerns about energy costs than owner occupiers. Scott and Powells [75] also found that hydrogen affordability presented the greatest barrier to social acceptance for survey participants in a region characterized by socio-economic deprivation and a legacy of industrial and economic stagnation.

Evidence from Australia and the Netherlands largely confirms that cost considerations are a priority (see Table 11). Beyond these findings and recent insights on consumer perceptions of hydrogen costs in the context of the HyDeploy [87] and H21 projects [69], there is little concrete evidence of the public's willingness to pay for domestic hydrogen. Whether consumers actively or passively accept hydrogen in their homes [153], the public should be willing to pay for new appliances, otherwise a transition is unlikely to take place without government mandates [284]. A case in point is the UK transition from 'town' gas to natural gas (1960–1977) [307], which took place during a command and control economy [302].

4.4. Barriers to community acceptance

4.4.1. Spatial dynamics of hydrogen communities in the UK

At present, it remains unclear how the transition to domestic hydrogen should be managed to account for socio-economic differences across the housing stock and problems of fuel poverty [75]. Confronting this knowledge gap is especially pertinent in the UK context, since the first wave of hydrogen projects will be deployed across industrial cities characterized by disparate economic and social geographies [69,75].

Table 11
This table provides evidence on public perceptions of hydrogen cost factors. Given mixed reports in the literature, cost concerns and barriers may prove place-specific and context dependent.

Study	Findings
[68]	• High levels of public support for developing Australia's hydrogen economy rested on the promise that regional industrial projects would deliver cost-competitive prices to consumers
[69]	• Relatively low levels of concern among UK survey participants given the scenario that hydrogen resulted in an estimated 7% increase to their gas bill • Concerns were still raised about the need to invest in new appliances for heating and cooking
[75]	• Grievances over high energy bills and low wages rendered around two-thirds of UK respondents as unable to absorb potentially higher prices for hydrogen, even if they expressed willingness to pay more for it
[83]	• 67% of Dutch respondents would be willing to use blended hydrogen if the switchover required a one-time changeover cost of €100 • 45% of respondents supported the use of blended hydrogen provided its running costs did not exceed those of natural gas by more than 10%
[86]	• French consumers were prepared to pay €100–136 to be more self-sufficient via stationary hydrogen-based storage systems, but they were not prepared to pay more for other attributes related to this switch
[87]	• Costs presented the main barrier to consumer support for hydrogen, with 77% of UK respondents unable and/or unwilling to pay higher energy bills
[88]	• Limited willingness to pay more for gas bills in Australia, with strong financial pressures already straining most household budgets
[123]	• For every £100 currently spent on home heating, people facing financial hardship were prepare and those financially secure were prepared to pay £102 and £111 for hydrogen (the mean response was £108)
[128]	• Participants indicated that increased long-term costs would lead to a comprehensive rejection of a transition to hydrogen

[19] Point 7 in the Ten Point Plan for a Green Industrial Revolution [262].

While GDNOs are strategically targeting these locations due to their competitive advantage for converting to hydrogen homes [153], this deployment trajectory raises governance challenges concerning consumer choice and rights [302].

The spatial dynamics of the UK hydrogen conversion – characterized by a notable degree of exclusivity given that around four million households (~15%) are located off-grid [308] and targeted deployment in proximity to industrial clusters [269] – amplifies the challenge of securing distributional justice. Taking the example H21 Leeds City Gate project, the capital cost of converting the gas network to hydrogen was estimated at £2.05 billion, with an annual operational cost of £139 million [302]. It was calculated this would result in an increase of around 1% to all consumer bills if the costs were shared nationwide [302]. It has also been shown that the estimated costs of decarbonizing the Welsh housing sector vary significantly according to tenure and status [309]. Average investment required per home ranging from £35,984 for fuel poor housing and £24,000 for social housing, to £4,700 for the private rented sector and £4,525 for owner occupiers [309]. Moreover, socially disadvantaged households lack opportunities to improve the envelope of their building and remain limited in their choice about energy technologies [72].

In addition to the issue of "equality of access to, and resultant efficiency of infrastructure, in the context of both location and housing type" [72], consumers may face practical and economic challenges should they wish to opt out of adopting hydrogen following a unilateral network switch [302]. If this option proves unviable it may contribute to a lack of equity between communities. The geographical nature of the roll-out could exacerbate issues of fuel poverty, especially if households excluded from the hydrogen transition are left facing higher energy bills [302]. From an energy equity perspective, private renters may face being locked into decisions made by landlords, while off-grid, rural communities could be doubly excluded from the energy transition since they may lack access to hydrogen networks or electrification [72]. This risk has been stressed by the Scottish Government, given that the combination of living off-grid and in a hard-to-treat property is an amplifier of fuel poverty, which means future heating solutions in Scotland need to be rural-proofed [310,311].

4.4.2. Public perceptions of community acceptance

Hydrogen acceptance could prove highly place-specific, whether at the country, regional, or local scale [123]. In Japan, consumer confidence and social acceptability increased for residents with a HFS in their local area [104]. In contrast, acceptance levels were lower for Germans for hydrogen infrastructure implemented in their neighborhood, highlighting the potential for NIMBY opposition [103]. However, Damette et al. [70] failed to find a significant effect for consumer opposition in relation to hydrogen energy storage systems being implemented at the neighborhood level in France. Martin et al. [86] observed that Australians were more willing to support a hydrogen production facility in their local area if dedicated to domestic use rather than for export, regardless of location or area type. Citizens of Leeds also expressed moderate to high levels of acceptance for hydrogen as a stimulus for developing a local green economy [123]; supporting the notion that local industries should be set up to produce hydrogen with local people support these developments.

Decisions regarding the distribution of costs could prove decisive to whether the hydrogen transition materializes in a socially acceptable way. Scholars have flagged the need to address how the costs of domestic hydrogen can be socialized equitably, while the transition is governed in a way that accounts for potential conflicts regarding consumer choice and rights [72,75,302]. Examining emotional responses to the first HFS in the Netherlands, Hujits [117] reported a stronger feeling of anger when higher levels of procedural and distributional injustice were perceived by citizens. Perceived unfairness also gave rise to feelings of fear, as did concerns around safety and risk which were heightened by a lack of prior awareness of the HFS. However, few studies have examined aspects of energy justice linked to the hydrogen switchover such as the distribution of costs [75] and potential impacts on vulnerable households [72].

Addressing energy vulnerabilities, Scott and Powells [87] highlighted public concern about the prospect of low-income households becoming further disenfranchised if hydrogen leads to higher energy costs. Consumers appear somewhat attuned to the importance of accounting for households with vulnerable or immobile occupants, while also acknowledging that appliances should be adapted for those with special needs [42,69]. When presented with a hypothetical hydrogen trial for around 300 homes, focus group participants raised concerns about the welfare of vulnerable members of the community such as the elderly and young, and those with health conditions or disabilities [42]. Worries were heightened for the switchover period, which could see households disconnected from the gas grid for up to two weeks.[20] Even if the switchover took place during the summer months, respondents stressed this would not offset the need for heating and hot water.[21] Split perspectives have also been reported, with 39% of respondents unconcerned about being disconnected from the gas grid for a few days, compared to 34% expressing concern [122]. Interestingly, Fylan et al. [69] noted that survey respondents assumed that the period of disconnection from the gas grid might be a few hours, as opposed to several days.

4.5. Barriers to behavioral acceptance

4.5.1. Public perceptions of the lived experience of heating and cooking

As a domestic energy technology, hydrogen will bring new experience and meaning into the daily practices of heating and cooking [75]; reflecting the notion that human activity revolves around a "shared practical understanding" that is 'embodied' and 'mediated' by surrounding 'materialities' [312]. Such activities will form "part of the ongoing reproduction of bundles and complexes of social practice" that shape the energy transition [165], with this 'material participation' offering a mechanism to cultivate the kind of 'energy citizenship' needed to accelerate the uptake of low-carbon technologies [123,313]. This focus reflects how the expediency of daily life may underpin hydrogen acceptance across different social geographies [178].

To date, there has been little public engagement with hydrogen homes in terms of testing appliances. Consequently, there is limited evidence on behavioral barriers compared to other acceptance dimensions, with researchers relying on survey results from hypothetical scenarios. Adopting a social practice approach, Scott and Powells [60] provided participants with simple pieces of information regarding the material and socio-technical properties of hydrogen and asked how these properties might impact their existing hob and boiler practices. The study found that 60% of participants would be 'slightly less comfortable' or 'much less comfortable' using hydrogen for their heating and cooking activities, while only 20% of participants believed 'it would make no difference'. This finding is noteworthy since same authors previously reported that UK consumers perceived the potential impacts on their use of appliances and the lived experience of heating and cooking to be negligible [87]. The above viewpoint was echoed by Australians [68] based on the understanding that hydrogen gas is expected to provide a fast, quiet and unintrusive domestic heating system that provides a close substitute for natural gas [121]; causing minimal disruption to consumer habits compared to alternatives such as heat pumps [314].

[20] The welfare of pets was also raised as a concern.

[21] A potential technical solution to reduce conversion times could be designing new hydrogen boilers to share a common backplate with existing natural gas boilers [67].

4.5.2. Divergence in public perceptions of hydrogen heating and cooking

Closer examination suggests that consumers are more likely to reject changes to hob practices, which may result in divergent decarbonization pathways for cooking and heating [60]. This could be attributable to the contrasting 'socio-material nature' of the two activities. Boiler practices (heating and hot water) are typically seen as 'detached', 'invisible' and 'backgrounded', whereas cooking is a distinctly 'intimate', 'visible' and 'foregrounded' activity, which makes kitchen activities more susceptible to disruptions and safety complications [60]. Consequently, 42% of participants believed hydrogen would bring no change at all to their heating practices, compared to 13% expecting a 'significant' or 'complete' change, whereas 30% of respondents anticipated 'significant' or 'complete' change to their cooking practices.

Based on these findings, it is apparent that failure to adequately account for implications related to the lived experience of hydrogen homes, characterized by a potential divergence between heating and cooking practices, would significantly hamper the efficacy of the domestic hydrogen transition. Nonetheless, it should be borne in mind that gas may be the preferred cooking fuel depending on national and cultural context [86]. Overall, consumers are mainly concerned that a switch to hydrogen appliances will deliver the same heating and cooking experience as natural gas in terms of functionality, appearance, and maintenance requirements [42] without compromising safety [60,75], however, limited data has been generated to decompose perceptions regarding potential behavioral impacts.

5. Discussion

Section 4 synthesized and distilled the empirical data on public perceptions of the hydrogen transition, and more specifically, hydrogen homes. Based on studies presented in Table 1 and supporting evidence, this section firstly ranks the critical factors of domestic hydrogen acceptance (see Table 12), before discussing research avenues and measures for overcoming barriers to domestic hydrogen acceptance based on the key findings.

5.1. Overcoming barriers to attitudinal acceptance

It is evident that attitudinal acceptance will be required if hydrogen is to compete with alternative low-carbon options such as heat pumps [121]. However, the dynamics of socio-psychological barriers concerning knowledge, awareness, and perceptions of hydrogen remain poorly understood since few studies have experimented with different types of information provision including colored information [70,86,226]. Moreover, few scholars have examined whether information provision regarding issues such as energy justice and fuel poverty may influence hydrogen acceptance [75]. At present, it remains unclear to what extent educating the public about hydrogen may yield dividends in terms of appeasing safety concerns and risk perceptions [75,86,87,121].

As a starting point, more social science research should be dedicated to assessing how neutral views based on limited knowledge and awareness may be converted into informed views of hydrogen, as a safe alternative to other residential heating and cooking technologies. Future studies should pay close attention to testing the effects of providing consumers with factual or hypothetical information, while assessing the impact of hydrogen and energy literacy on social acceptance. Overall, information provision should target understanding around priority issues such as the safety, cost, and performance of hydrogen appliances, but also extend to wider questions concerning the economic, environmental, and social impacts of hydrogen's role in the energy transition. Following Williams et al. [121], researchers should also examine whether information provision is more effective when limited to details about a single technology.

There is an underlying risk that the public may view the prospect of hydrogen appliances neutrally; unless more inroads are taken to publicize the technology, while clearly articulating its potential costs,

Table 12
This table provides a ranking for the critical factors of domestic hydrogen acceptance based on the literature in Table 1. At this stage of the transition, the foremost critical factors to social acceptance for hydrogen homes are financial costs, and knowledge and awareness.

Acceptance dimension	Critical factor	Ranking category	Description of key findings on hydrogen acceptance factors
Market	Financial costs	Critical	• Critical concerns over cost barriers (purchasing and/or running costs), and potential lack of government subsidies, financial incentives or compensation [42,68,69,75,77,86,87,89,122,123,128]
Attitudinal	Knowledge and awareness	Critical	• Very limited public knowledge and awareness of hydrogen and its production methods [42,68–70,77,86–89,121,123,130] • Very limited knowledge of hydrogen properties and its uses, or technical features of hydrogen technologies [60,68,70,77,86,88,89,121,123,130]
Community	Disruptive impacts	Major	• Major concerns over the disruptive impacts of the switchover [42,77,86,121,122,128]
Community	Distributional justice	Major	• Major concerns over distributional injustice including spatial inequities and disenfranchisement of low-income groups or those in fuel poverty [42,69,72,87]
Socio-political	Consumer disengagement	Major	• Limited consumer engagement with the energy sector beyond switching energy supplier [69,77]
Behavioral	Lived experience of cooking	Major	• Limited understanding of the lived experience of cooking [72] • Major concerns over potential disruption to the lived experience of cooking [60]
Attitudinal	Safety perceptions	Significant	• Significant concerns over safety and risk factors [60,77,86–88,128] • Significant concerns over hydrogen's invisible flame and odorless nature [42,60,68,86] • Negative perceptions or worries concerning the combustibility and flammability of hydrogen [42,60,77,86,87] • Significant concerns over hydrogen storage and carbon capture [42,68,69,88,122]
Socio-political	Environmental impacts	Significant	• Significant concerns over the impacts of hydrogen production to climate and the environment [42,68,77,86,123] • Limited support for blue hydrogen (SMR + CCS) as a long-term production strategy and/or an expressed preference for green hydrogen [68,70,88,123,128]

(continued on next page)

Table 12 (*continued*)

Acceptance dimension	Critical factor	Ranking category	Description of key findings on hydrogen acceptance factors
Socio-political	Public trust	Significant	• Skepticism regarding the tangibility of environmental benefits [42,68,69,77,86] • Limited public trust in the gas industry, government, local MPs and/or media [68,86–88] • Skepticism about government actions and intentions [42,88]
Community	Procedural justice	Moderate	• Moderate concerns over energy vulnerabilities, fairness, and related aspects of procedural justice [42,69,72,77] • Moderate concerns regarding realistic timeframes and/or transparency regarding the switchover and transition [42,68,69,121]
Market	Technology choice	Moderate	• Moderate concerns over potential lack of technology choice for decarbonization of heating and cooking [68,69,77,123]
Attitudinal	Affective response	Moderate	• Neutral perceptions of hydrogen across much of society [68,87,89]
Market	Economic impacts	Moderate	• Moderate concerns over reliability of energy supply/ energy security [86,122]
Behavioral	Lived experience of heating	Minor	• Limited understanding of the lived experience of heating [72] • Minor concerns over potential disruption to the lived experience of heating and system familiarity [60,121]

benefits, and risks. Indeed, Scovell [12] concluded that these factors could prove the most influential to HET acceptance, highlighting the need for stakeholders to maximize communication of perceived benefits over costs and risks. Furthermore, low-carbon behavioral practices appear to be positively correlated to environmental awareness [315,316] and citizen particpation [138,313], reinforcing the need for public engagement and awareness campaigns to help establish a positive reputation for hydrogen [77].

Attitudinal factors (see Fig. 4) should be incorporated into the design of future communication campaigns targeting hydrogen acceptance [76]. Overall, there is a growing demand for factual information and clear evidence [42]. The public is interested in understanding significantly more about the financial and environmental implications of hydrogen, as well as the wider costs and benefits of the transition, with a desire for clearer information about safety issues and realistic timeframes [88]. Following Whitmarsh et al. [175], the positive public perceptions are more likely provided that "safety, efficiency, and cost criteria" are met. In turn, resources should be allocated to articulating how the utility and added value of hydrogen-fueled appliances may outweigh potential disruptions and drawbacks compared to alternative technologies [121,317,318].

Information dissemination should be targeted in a coordinated and strategic way, since "intense promotional campaigns" may not pay dividends if misdirected at consumers strongly opposed to hydrogen [115]. Key stakeholders such as government agencies, local authorities, energy companies, the gas industry, and media outlets, should communicate information to specific communities and households to increase the scope for social acceptance and counteract the risk of systemic public mistrust [24]. This could include middle-aged or retired women without higher education or technical knowledge, as well as unemployed or retired men who are skeptical about new technologies.

Finally, it has been documented that socio-structural factors such as age, gender, education, employment status, environmental values, and technical knowledge may drive or constrain hydrogen acceptance, however, the potential importance of these variables remains unclear. Future survey studies should aim to quantify the statistical significance of socio-structural factors on hydrogen knowledge, awareness, perceptions, and attitudes. In turn, attention should be paid to evaluating the extent to which knowledge and awareness may shape people's perceptions of and attitudes towards hydrogen-fueled appliances.

5.2. Overcoming barriers to socio-political acceptance

Socio-political acceptance rests on a range of factors including consumer engagement in energy markets, and public perceptions of hydrogen production pathways, environmental impacts, and the broader energy transition, as well as public trust in the emerging hydrogen landscape including its key actors and stakeholders. As a first

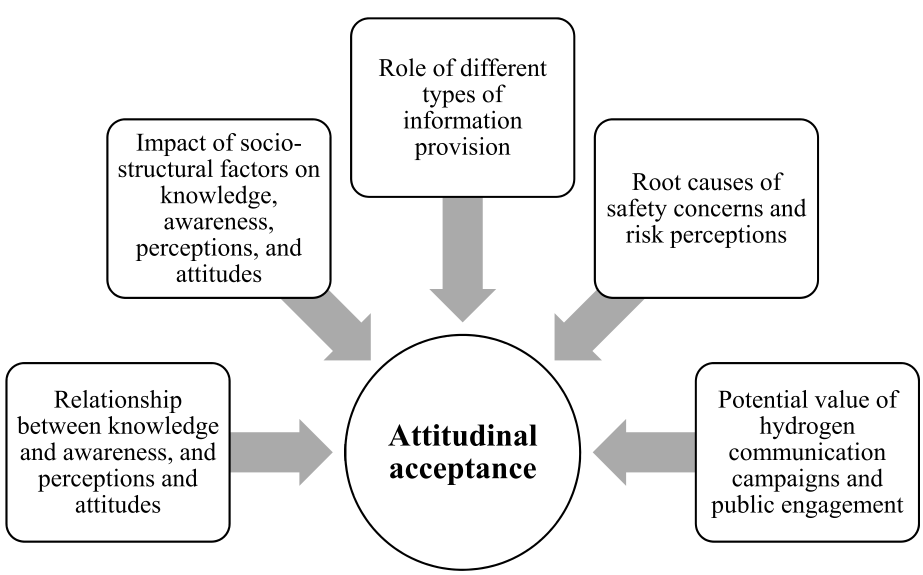

Fig. 4. This figure illustrates five key research areas for advancing attitudinal acceptance.

step this should translate into quantifying the impact of socio-structural factors on public/consumer trust in key actors and stakeholders within the hydrogen landscape. Based on the evidence presented in section 4.2, the literature should provide a deeper understanding of consumer preferences for hydrogen production pathways, which includes gauging if a transitional role for blue hydrogen is likely to be supported by the public. Additionally, studies should explicitly focus on how the public perceives hydrogen's role in reaching net zero and curbing fuel poverty.

Hydrogen acceptance studies should account for energy supply dynamics at the household level [70], as well as the potential for community-owned hydrogen projects [319]. In this respect, there is a parallel need to examine consumer attitudes towards centralized and decentralized hydrogen, electrification, and energy security. In the most recent analysis of acceptance barriers in the Australian context, it is noteworthy that reliability of energy supply ranked second behind safety [86]. Furthermore, this review has noted the potential importance of consumer disengagement in energy markets and experience with energy suppliers. A natural step forward is to test whether attitudes towards the hydrogen switchover and transition may vary according to the nature and level of consumer disengagement (see Fig. 5). Moreover, scholars should examine whether the public perceives national hydrogen strategies to be socially acceptable in respect to timeframes, costs, benefits, and risks. Researchers could also examine if consumers have any preferences regarding energy supplier when faced with the prospect of a hydrogen switchover.

5.3. Overcoming barriers to market acceptance

As described in section 4.4, market acceptance will rest on how barriers are addressed at both the macro- and micro-level. To date, there is limited evidence comparing public perceptions of cost barriers related to initial investment, running, and maintenance costs of hydrogen appliances. While some basic findings have been presented, an extensive knowledge gap remains regarding the potential interactions and trade-offs between purchase and running costs when it comes to domestic hydrogen acceptance. Notwithstanding, it is apparent that underlying financial factors will play a fundamental role in dictating decision-making at the household level and the overall trajectory of the switchover.

Studies on hydrogen futures [29] should continue to examine market acceptance at the macro-scale in relation to the wider hydrogen economy, as illustrated in the Australian context [68,86]. A starting point would be to understand public attitudes toward the timeline and trajectory of hydrogen strategy plans, accounting for sectoral priorities (industry, power, transport, and domestic), and temporal and spatial preferences. Moreover, clearer insights are needed to establish if consumers without access to hydrogen would be willing to support and pay for the switchover, and whether this may hinge on how socio-economic benefits are distributed across society. Following Scott and Powells [75], scholars should address uncertainties at micro-scale regarding society's ability and willingness to pay for the costs of the domestic hydrogen transition; examining how willingness to pay for hydrogen may vary according to housing tenure (see Fig. 6). This can help establish what kind of financial risks different segments of the population and housing stock may tolerate, and the rationale or justification behind such decisions.

Further questions should also be asked about how consumers perceive the importance of choice when it comes to heating and cooking technologies. More studies are needed to better understand whether consumers see hydrogen as promoting a smarter and more efficient heating or cooking system for low-carbon homes, compared to a like for like substitute for natural gas. This translates to the research community ensuring that heating and cooking are treated as distinct dimensions of the domestic hydrogen transition [60]. Notably, Drożdż et al. [115] found that nearly 70% of survey respondents valued increased market choice for electric car models as a spillover benefit of a scaling up in HFCVs, which could prove an interesting point for the residential context. Questions should be put to the public about how they see hydrogen fitting into the overall landscape for low-carbon technologies, and whether it is perceived as a win-win, or 'no regrets' development.

5.4. Overcoming barriers to community acceptance

The feasibility of the transition and visions for hydrogen futures [29] may rest on how the foundations of social acceptance are laid in proximity to hydrogen hubs around industrial clusters, reinforcing why research efforts should be concentrated on those communities where early hydrogen activities are planned [77]. Given the spatial dynamics of the emerging hydrogen economy in countries such as the UK, researchers should examine community acceptance in respect to industrial heritage, regional regeneration, and employment opportunities.

To date, the influence of past impacts such as industrial blight, air pollution, and unemployment in socially deprived areas, exemplified by Teesside in the North East of England [320], remains largely unattested in the context of domestic hydrogen acceptance [75]. Future studies should engage with citizens from representative parts of the country

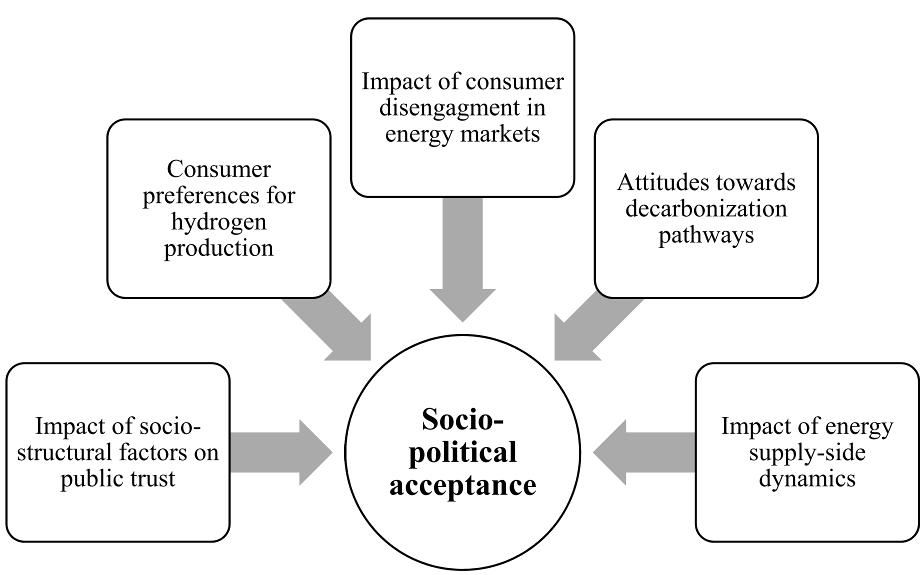

Fig. 5. This figure illustrates five key research areas for advancing socio-political acceptance.

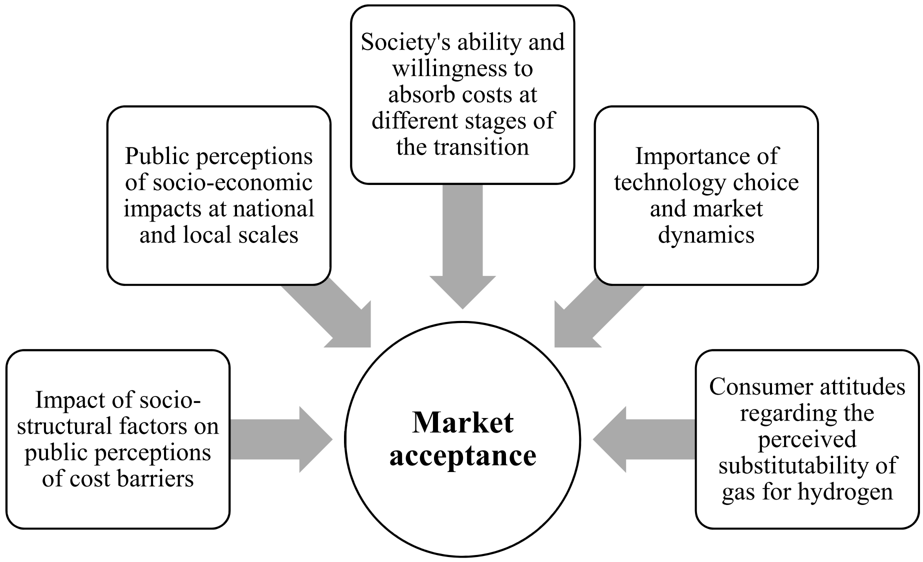

Fig. 6. This figure illustrates five key research areas for advancing market acceptance.

including communities located in urban areas in proximity to prospective hydrogen hubs and those located in off-grid rural areas, as well as population groups that fall in between these two ends of the housing spectrum. The rationale for this approach is to find out if, and to what extent, consumers excluded from the switchover may be willing to accept the hydrogen transition. Accordingly, it should become clearer how the spatial exclusivity (see Fig. 7) of the domestic hydrogen transition is shaping social acceptance [153], and whether support levels correlate to access, use, and choice.

Hydrogen's unique spatial dynamics, coupled to growing awareness about fuel poverty [321,322] make it imperative that policies and roll-out strategies strive to deliver energy justice. Sound policymaking grounded in procedural justice should pay close attention to the distribution of socio-economic costs and benefits, while factoring the welfare of vulnerable members of society into these calculations [68,87]. Otherwise, deficits in either justice dimension could potentially derail the social acceptance of domestic hydrogen, weakening the net zero agenda and contributing to further recognition injustice in the guise of fuel poverty. Given that average investment costs for heat decarbonization could prove significantly higher for households in fuel poverty, governments will need to design and implement policies to deflate socio-economic barriers. However, internalizing distributional justice into strategy plans remains compounded, since the economic costs of the hydrogen transition are difficult to forecast and quantify [87,323].

Accounting for these uncertainties, there is a need to undertake "fine-grained qualitative research" at the community and household level to better understand citizen perspectives on how changes to the energy system may impact vulnerable groups [87]. To engage with these barriers, future research should account for the immediacy of local conditions [178], as well as "the diversity and dynamics" of local communities [88]. As a starting point, research efforts should be dedicated to understanding how the hydrogen transition may impact vulnerability demographics over time, given that different deployment pathways are likely to impact the distribution and intensity of fuel poverty [72].

5.5. *Overcoming barriers to behavioral acceptance*

To engage with behavioral barriers, it is important to comprehend the ways in which different energy cultures may impact hydrogen acceptance at the household level. In addition to evaluating the

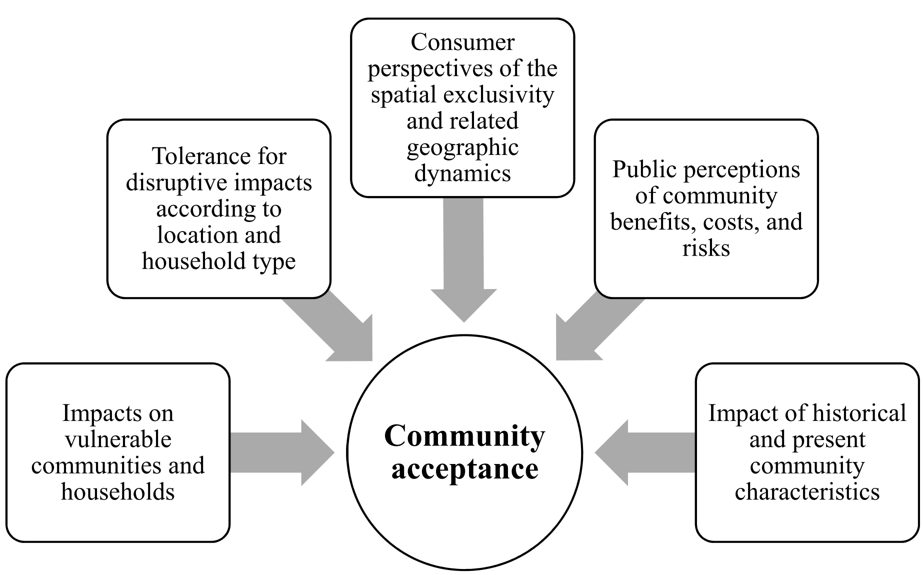

Fig. 7. This figure illustrates five key research areas for advancing community acceptance.

importance of technology choice and consumer rights, studies should flesh out how existing energy cultures could shape the hydrogen transition, paying specific attention to the interactions between cultural and behavioral dynamics. In parallel, it should be recognized that people may have limited agency since the surrounding material culture may be beyond their control. Decarbonization pathways may be decided at the national or regional level, leaving consumers with no choice about whether to remain connected to the gas grid and which fuel to use.

Future studies should also examine consumer perceptions regarding the impact of hydrogen on domestic energy practices, for example, testing to see if preferences between hydrogen appliances and other low-carbon heating technologies vary according to cultural factors including heating habits and cooking practices (see Fig. 8). Researchers should purposefully explore the potential relevance of energy cultures to domestic hydrogen acceptance. For example, comparisons between consumers familiar with low-carbon and smart technologies, versus consumers who are more disengaged with renewable and smart technologies.

Foremost, studies should address the potential impact of hydrogen homes on the energy practices of households in fuel poverty. Results already caution that misconceptions regarding the disruptive impacts of the switchover period could act as a significant barrier to acceptance. This underscores the need for transparency in information dissemination if social acceptance is to be gauged accurately, without inviting heightening risks of energy injustice. While all these points are critical to better addressing and overcoming barriers to behavioral acceptance, more tangible advances in understanding will only be possible once consumers begin to test hydrogen appliances at demonstration sites and during local trials. Already there is a desire for consumers to see the technology working, or to at least hear from others with experience of hydrogen heating and cooking systems [42].

6. Conclusions

This review paper was formulated on the premise that securing social acceptance for hydrogen technologies, especially in the domestic context, is imperative to the energy transition and the realization of a global hydrogen economy. A socio-technical systems approach was employed to better understand the human dimension of adopting hydrogen appliances for home use. Key findings have been presented in Table 12 and Figs. 4–8. This section serves to highlight the main contribution of this output to the hydrogen futures and energy transitions literature.

This review largely supports the notion that the most common barriers to renewable or low-carbon energy adoption are financial concerns, a lack of information about the technology, and socio-structural factors [324]. Evidence also suggests that social acceptance could hinge on hydrogen's potential impacts on household energy vulnerability [72], and whether consumers are granted sufficient lead time to complete the switchover [121]; in an informed and planned way [68] which minimizes disruptive impacts. In this sense, transitioning to hydrogen homes may prove comparable to the installation of domestic micro-generation technologies [134], given that both technology pathways call for social acceptance and public engagement to support large scale adoption [318]. Accordingly, households should be prepared to cover installation costs, coordinate with technicians during the changeover, and accept minor behavioral changes when switching to a hydrogen home. However, for this level of willingness to ensue, the role of information provision and public awareness campaigns must be thoroughly investigated and better understood.

This paper has demonstrated the importance of engaging with hydrogen acceptance at the attitudinal, socio-political, market, community, and behavioral level, while accounting for interactions between these five dimensions through a socio-technical systems perspective. Attitudinal acceptance, resting on how knowledge and awareness shape perceptions and attitudes, has been shown to underpin other acceptance dimensions [153]. To date, hydrogen technologies are yet to permeate the public consciousness in a meaningful way, owing to a lack of public awareness and knowledge. This review adds weight to the argument that neutral impressions of hydrogen are unlikely to be overturned, and converted into positive perceptions, absent of a strategic plan to confront acceptance barriers head on. For this strategy to be engineered, social scientists have a duty to pioneer a new wave of mixed methods research on domestic hydrogen acceptance; harnessing the power of statistical evidence from survey studies, and qualitative insights from interviews and focus groups, to increase the richness of data on public perceptions and consumer preferences.

At the socio-political dimension, there is a growing need to understand emerging views towards national hydrogen strategies, with a focus on production pathways and trust factors. *Consumer engagement in energy markets and stronger public trust in key stakeholders will help support social acceptance as the hydrogen transition unfolds.* Market acceptance rests on understanding how consumers perceive cost barriers, which translates to quantifying willingness and ability to pay for prospective hydrogen appliances and the switchover. The analysis highlights that affordability may prove *the most critical barrier to the large-scale adoption of hydrogen*

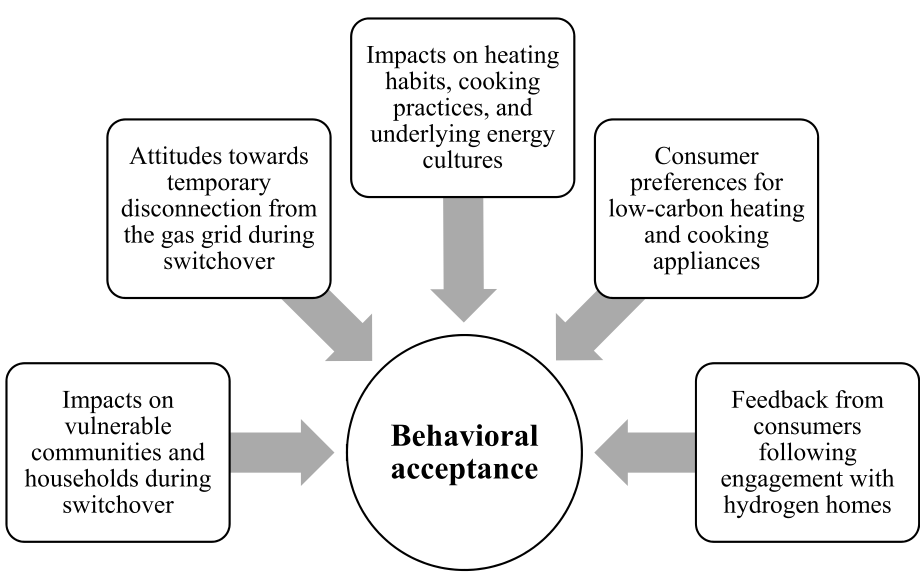

Fig. 8. This figure illustrates five key research areas for advancing behavioral acceptance.

homes.

Community acceptance calls for engagement with dimensions of energy justice, supported by a roadmap for minimizing disruptive impacts and energy vulnerabilities, which requires a comprehensive mapping of socio-structural factors such as housing tenure. Careful attention will need to be paid to communicating and minimizing the *disruptive impacts of the switchover, while alleviating concerns over distributional and procedural injustices. As a starting point, the promise of economic, environmental, and community benefits must be communicated and fulfilled to endorse the value of hydrogen homes.* Finally, studies on behavioral acceptance must shift from the hypothetical to the actual, as consumers begin to test hydrogen appliances in demonstration homes. Alongside bringing hydrogen into the public consciousness, this will enable a more legitimate understanding of the lived experience of hydrogen heating and cooking, as well as technology choice. This engagement could feasibly lead to a different ranking of critical factors. This holds equally true for other identified and potential factors, given that the five dimensions of hydrogen acceptance present a dynamic and co-evolving phenomenon [153].

To strengthen hydrogen's social standing [78], it is imperative that future studies adopt a socio-technical systems perspective; dedicated to elevating the importance of social acceptance in configuring the evolution of hydrogen technologies for the residential sector. Visions for hydrogen futures, the promise of national hydrogen economies, and the feasibility of a domestic hydrogen transition in candidate countries may rest on how this potentiality is facilitated and strengthened by key stakeholders to overcome barriers to attitudinal, socio-political, community, market, and behavioral acceptance.

Credit author statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft, **Nazmiye Balta-Ozkan**: Conceptualization, Writing – review & editing, Supervision, **Ali Nabavi**: Writing – review & editing, Supervision

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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.

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