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Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance?

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HIGHLIGHTS

- The UK public appears receptive to the launch of a national hydrogen strategy.
- Negative perceptions of the twin-track production approach stem from misconceptions.
- Blue hydrogen requires explanation and justification to preempt social resistance.
- Consumer buy-in hinges on access to reliable and transparent sources of information.
- Hedonic and cost concerns typically outweigh climate change considerations.

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ABSTRACT

National hydrogen strategies are emerging as a critical pillar of climate change policy. For homes connected to the gas grid, hydrogen may offer an alternative decarbonisation pathway to electrification. Hydrogen production pathways in countries such as the UK will involve both the gas network and the electricity grid, with related policy choices and investment decisions impacting the potential configuration of consumer acceptance for hydrogen homes. Despite the risk of public resistance, be it on environmental, economic, or social grounds, few studies have explored the emerging contours of domestic hydrogen acceptance. To date, there is scarce evidence on public perceptions of national hydrogen policy and the extent to which attitudes may be rooted in prior knowledge and awareness, or open to change following information provision and engagement. In response, this study evaluates consumer preferences for a low-carbon energy future, wherein parts of the UK housing stock may adopt low-carbon hydrogen boilers and hobs. Drawing on data from online focus groups, we examine consumer perceptions of the government's twin-track approach, which envisions important roles for both 'blue' and 'green' hydrogen to meet net zero ambitions. Through a mixed-methods, multigroup analysis, the underlying motivation is to explore whether the twin-track approach appears compatible with hydrogen acceptance. Moving forward, hydrogen policy should ensure greater transparency concerning the benefits, costs, and risks of the transition, with clearer communication about the justification for supporting respective hydrogen production pathways.

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Nomenclature

CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CHP	Combined heat and power
EU	European Union
GDNO	Gas Distribution Network Operator
HETs	Hydrogen energy technologies
HFCVs	Hydrogen fuel cell vehicles
HFSs	Hydrogen fuelling stations
MMR	Mixed methods research
RESs	Renewable energy sources
RETS	Renewable energy technologies
UK	United Kingdom

Introduction

The notion of a global 'hydrogen economy' [1,2] and associated idea of a 'hydrogen city' [3] can be traced back to the 1970s and 1980s, with these concepts taking root in academic research, mainstream literature, and the political arena during the early 2000s [4,5]. During this time, scholars have debated and scrutinised the potential role of hydrogen in the global energy transition [6–10].[1] As climate change-related pressures continue to mount, [11–13], the discourse has increasingly shifted towards developing a 'sustainable hydrogen economy' [4,14,15], as reflected by a recent wave of national policy strategies and targets [16,17].

Hydrogen's attractiveness to policymakers and the energy industry stems from its unique attributes, as a potential driver of energy security [18,19], international competitiveness [19], large-scale emissions reduction [18–21], and improved air quality [18,19,21], especially via industrial decarbonisation [22,23]. Critically, hydrogen may help manage the intermittency of renewable energy sources (RESs) [24] by providing a means to store excess electrical energy [25–27]. Hydrogen is especially coveted in countries with extreme import dependency such as South Korea [28]. Moreover, the most recent gas crisis [29], coupled to ongoing market volatility and political instability linked to the Russia-Ukraine conflict [30–33] has intensified a new 'dash for hydrogen gas' in Europe to counteract energy security risks [34,35].

Notably, the European Union (EU) has growing ambitions to scale up hydrogen capacity [36–38], with European Commission Vice President, Frans Timmermans, declaring plans to position Europe at the forefront of the 'hydrogen revolution' [39]. Specifically, the EU aims to develop a hydrogen backbone, composed of dedicated pipelines spanning thousands of kilometres and cutting across multiple Member States [40–42]. Similarly, the United Kingdom (UK) is seeking opportunities for cross-border hydrogen trade with Europe [40,43]. Foremost, National Grid's Project Union entails a 2000 km hydrogen network linking major UK industrial clusters which could help facilitate this ambition [44].

Visions for a national hydrogen economy rest strongly on the role of industrial clusters in the energy transition [45,46], envisioning a transformation towards industrial 'SuperPlaces' [47] and 'hydrogen clusters' [48].[2] Industrial transformation, as exemplified through the scaling up interconnected hydrogen backbones and clusters, may prove decisive to shaping the geopolitics and international governance [17] of future markets for hydrogen energy systems [49]. In countries historically reliant on natural gas such as the UK [50,51], hydrogen may also provide a means for decarbonising the residential sector via low-carbon appliances for heating and cooking [52–54]. Released in August 2021, the UK Hydrogen Strategy [55] details how 'hydrogen homes' may form part of a hybrid strategy for residential decarbonisation, alongside heat pumps, district heating and other low-carbon technologies. Notably, the strategy supports plans to scale-up hydrogen trials in targeted localities [56,57]. To better contextualise activities around the emerging hydrogen economy, Table A1 summarises recent developments in UK hydrogen policy (see Appendix A).

Alongside policy commitments and market mechanisms [58], realising prospects for a full-scale hydrogen economy [59–61] and hopes for hydrogen homes [62] will rest on understanding and responding to public perceptions [63–65]. As Dumbrell et al. [66] explain, "the transition involves difficult choices that must be technically feasible, relatively safe, economically rational, and accepted by the public." Consumer buy-in and broader social acceptance [21,67] are prerequisites for enabling technology adoption [68], and developing a 'just hydrogen economy' [69] in support of a socially equitable energy transition [23,70]. Similarly, Ren et al. [71] highlight the importance of integrating socio-political acceptability, alongside technological, economic, and environmental criteria, when evaluating the sustainability performance and suitability of hydrogen production technologies.

While the techno-economic feasibility of decarbonising the UK gas grid via hydrogen has been explored in different energy models for over a decade [72–75], social science research on domestic hydrogen acceptance [64,76,77] has only emerged within the last few years [78]. To date, most social science research has centred on data collected from online surveys [76,79–81], whereas qualitative research grounded in deliberative methods and participatory techniques remains scarce [52,62,82]. Mixed methods research (MMR) featuring a strong qualitative element is needed to meaningfully engage the public with hydrogen energy technologies (HETs) in an active way [19,82], while broadening social perspectives on prospective hydrogen futures and applications [83]. In response, this study draws on qualitative and quantitative data collected through 10 online focus groups, which intersected

[1] For example, Sovacool et al. [5] cautioned that the hydrogen economy may reinforce a pervasive 'energy culture', in which public and individual expectations coalesce around a fantasy future "where energy is abundant, cheap, and pollution-free." The Energy Cultures Framework [255] recognises that "distinctive clusters of knowledge, belief, behaviour and material objects (as held by individuals and groups) will have some bearing on the way energy is used, along with the more decentred influences."

[2] For example, among recent announcements, the 'Green Blue' action plan aims to decarbonize London's Thames Estuary via the development of a hydrogen ecosystem on land and water [278,279].

with key geo-economic and geo-political events affecting global energy markets and UK society [29,33].

The paper examines public perceptions of the UK domestic hydrogen transition and prospective production pathways. The aim of the research is to determine, (1) what is the existing level of hydrogen knowledge and awareness among UK consumers and what are their preferences for information dissemination; (2) what perceptions do consumers hold towards the UK government's 'twin-track' approach entailing blue and green hydrogen production pathways; and (3), how do consumers perceive the prospect of domestic hydrogen as part of the country's low-carbon energy future. While the first research question gauges attitudinal acceptance by evaluating individual and group levels of hydrogen knowledge and awareness [63,78], the remaining research questions engage with socio-political acceptance [84] by exploring consumer attitudes towards the hydrogen transition at the macro-level [63,78].

The stated aims contribute towards the main motivation of this exploratory study, which is to help steer future research and decision-making on the domestic hydrogen transition towards a socially acceptable pathway. The rest of the paper proceeds as follows. The next section contextualises the study by reviewing the hydrogen policy and acceptance literatures. The methods section describes the research design, distinguishing between the qualitative and quantitative components of the online focus group approach. Next, the results section presents the findings of the mixed-methods analysis, which are validated through a series of statistical tests to derive meta-inferences from both MMR strands. The penultimate section discusses the implications of the findings, while the final section concludes the study.

Literature review

This section reviews the literature on hydrogen production pathways and related energy policy alongside scholarly contributions which have placed 'hydrogen acceptance on the radar'. In doing so, we provide an overview of key developments in the hydrogen futures literature, as well as a more specific focus on findings related to knowledge and awareness of hydrogen, and consumer perspectives on hydrogen production technologies.

Hydrogen policy and production pathways

Reviewing the 'hydrogen futures' literature in the mid-2000s, McDowall and Eames [19] linked the drive towards a hydrogen economy with the emergence of stronger environmental values and greater support for social equity; reflected by the advent of energy decentralisation and the democratisation of RESs [85–88]. Notwithstanding, there are a range of 'technological architectures' (i.e. centralised, decentralised, and hybrid) underpinning the configuration of hydrogen production pathways in different countries and regions [83,89–91]. Technological architectures and associated policies may support a 'blue' hydrogen pathway [92], based on steam methane reformation (SMR) with carbon capture and storage (CCS); or alternatively, align with developing a 'green hydrogen economy' [93] based on production via electrolysis using renewable electricity [24,94,95]. Other production pathways – combining and balancing different hydrogen sources – are rapidly emerging as national hydrogen economies continue to evolve [8,23,96–98].

Currently, the status of blue and green hydrogen as competing or complimentary production sources varies across the globe [99,100]. For example, the Australian Government retains a technology-neutral or agnostic stance [66]. Meanwhile, Canada is exploring several hydrogen production pathways according to available feedstocks, energy inputs, and the feasibility of carbon capture, utilisation and storage (CCUS) across different regions and provinces [101,102]. By contrast, EU policy is more aligned to a green pathway [38], with ambitious commitments towards increasing electrolyser capacity in Spain [103], Germany [104], and France [105], among other Member States [106].

In the German context, evidence suggests that blue hydrogen is critical to enabling the transition to a green hydrogen economy, which rests on first decarbonising the power sector [107]. The same holds true in the UK context, wherein the equivalent of 300 GW of offshore wind power would be needed to meet forecasted hydrogen demand across the energy sector [108].[3] In response, the UK government is investing in both CCUS-enabled production and electrolysis, through its twin-track approach. In April 2022, the British Energy Security Strategy doubled the 2030 hydrogen production target to 10 GW, specifying that at least 50% should be sourced from electrolytic ('green') projects (see Appendix A). In February 2023, the government announced a consultation process for the Low Carbon Hydrogen Certification Scheme to help establish the sustainability criteria of hydrogen production, in view of strengthening market confidence and investment opportunities [109].

Policy support is needed to enable a role for blue hydrogen as a 'bridging technology' to help scale up green hydrogen methods [55,110]. However, the societal costs of pursuing this pathway must be understood and communicated [94] before new energy systems become path dependent [66] and 'locked-in' [111]. Critics of blue hydrogen suggest that social acceptance is likely to be an issue [112], given that its overall carbon and environmental credentials are less favourable than renewable-based hydrogen production [94,113]. It has been argued that the blue pathway may subvert the energy transition agenda [72,111], especially if problems, risks, and uncertainties around methane leakage rates [114,115], global warming potential [115,116], nitrogen oxides emissions [117,118] and other environmental impacts [119],[4] cannot be overcome or adequately understood. Relatedly, Cheng and Lee [120] developed a four-fold typology to evaluate the green commitments of national hydrogen strategies, finding that most countries aim to scale up production first before prioritising climate targets (i.e. 'scale first and clean later').

[3] Compared to an existing capacity of approximately 14 GW and a 2030 target of 50 GW.

[4] For example, particulate matter formation, terrestrial acidification, mineral resource depletion and freshwater ecotoxicity [119].

Ultimately, from a climate change perspective, hydrogen is "only as compelling as its feedstock supply" [121] and the management of system processes across the value chain [122]. Critically, Velazquez Abad and Dodds [123] undertook a global review of the green hydrogen policy developments, highlighting ways in which green hydrogen schemes must develop to meet stringent sustainability criteria.[5] More broadly, research on the hydrogen economy should adopt a whole-systems approach to better account for the sustainability impacts of HETs in terms of product life cycle and waste issues [19].

Hydrogen acceptance on the radar

Hydrogen acceptance presents a burgeoning research area, supported by a relatively rich literature spanning two decades [124–126]. Mapping developments in the hydrogen economy since the early 1970s, Yap and McLellan [127] acknowledge that HETs face similar challenges to more familiar RETs such as wind and solar [128] when it comes to establishing 'global acceptance'. Critically, the social aspects of the hydrogen transition should be examined to bridge the existing knowledge gap regarding consumer preferences for HETs [127]; serving as a mechanism to help support a sustainable hydrogen economy with end-user acceptance [129]. Responding to prior reviews on hydrogen acceptance [82,130,131], Agnoletti et al. [129] affirm this point by recommending a more 'human-driven' approach to increase the desirability of HETs. Similarly, Vallejos-Romero et al. [132] identify hydrogen acceptance and consumer willingness as critical factors for responding adequately to emerging market demands, with a primary view towards the green hydrogen value chain. This study follows in this tradition by advocating for the importance of understanding consumer attitudes when designing, augmenting, and diffusing HETs.

Overview of hydrogen futures literature

To date, hydrogen technology studies have focused mainly on transport applications [133–136], principally hydrogen fuel cell vehicles (HFCVs) [21,67,137–139], hydrogen buses [140,141], and related infrastructure such as hydrogen fuelling stations (HFSs) [142]. Mirroring this focus, early studies on public perceptions of HETs concentrated mostly on the transport sector [143–146], with this research stream consolidated by recent studies in South Korea [147–149], China [150,151], India [152–154], Japan, and Australia [155]. For example, in the Indian context, Kar et al. [154] reported a positive relationship between perceived environmental benefits such as carbon footprint reduction and intention to use HFCVs, while Harichandan and Kar [152] also found environmental consciousness to positively influence consumer acceptance for HFCVs. By the same token, higher levels of environmental concern may increase the adoption intention for HFCVs [152,156].

Literature reviews conducted by Emodi et al. [61] and Scovell [64] attest to the same trends, but also highlight the emergence of studies on domestic applications including hydrogen boilers and hobs, and stationary residential hydrogen fuel cells. For example, in their comparative European study (N = 7148) Bögel et al. [157] reported lower levels of acceptance for hydrogen fuel cell technologies compared to stationary hydrogen systems for home heating and electricity. Hydrogen studies in the German context have also shifted the focus towards understanding the dynamics between local and general acceptance [146,158,159]. Schönauer and Glanz [158] investigated the acceptance of local hydrogen pipeline infrastructure and general acceptance, finding lower levels of support for infrastructure implementation in one's own neighbourhood compared to hydrogen at large. Emmerich et al. [146] adopted a similar conceptual approach, operationalised through a structural equation model (SEM), which revealed higher levels of general acceptance for HFSs compared to community-level acceptance [84]. More specifically, environmental self-identity had a positive indirect effect on general acceptance, but a negative direct effect on local acceptance, which may be attributed to the disruptive impacts of HFSs on the local environment [146].

Compared to survey studies with a predominantly statistical focus [157,160,161], which include the aforementioned studies, qualitative research on domestic hydrogen acceptance is mostly limited to studies in the grey literature [162,163] or mixed methods analyses [80,164], which are more likely to be quantitatively driven [165,166]. One notable exception in the academic literature is the study of Sandri et al. [77], which involved a stakeholder workshop with energy experts and drew on a focus group style methodology (i.e. 'breakout sessions') to gauge views on the impact of domestic hydrogen on energy vulnerabilities in Australia. Relatedly, following an inductive analysis of stakeholder views – composed of publicly-available industry submissions to the National Hydrogen Strategy and community submissions in Victoria – Beasy et al. [167] flagged the importance of community acceptance in supporting Australia's hydrogen transition. Other important contributions to the social science discussion on domestic hydrogen include the research agenda proposed by Scott and Powells [52,76], which is rooted in a social practice theory approach [168]. Through this lens, cooking and heating practices entail complex socio-material characteristics, [52,169], which account for divergent residential lifestyles and practices [170,171].

Knowledge and awareness of hydrogen

Knowledge and awareness may prove critical to domestic hydrogen acceptance, especially in the early stages of the transition [78]. As argued by Sherry-Brennan et al. [172], pre-existing knowledge creates 'reference points'[6] to which consumers 'anchor' their perspectives of HETs. Within the hydrogen futures literature, it is well-documented how a lack of familiarity with the technology constrains end-user acceptance [132,173]. As summarised in Table 1, hydrogen

[5] The recent literature has tended to focus mostly on green hydrogen policy such as the need for standards and guarantee of origin schemes [123], and other policy support mechanisms such as subsidies for enabling grid-based green hydrogen production [94,280].

[6] The notion of 'reference points' can be traced to earlier work conducted by Ricci et al. [281].

Table 1 – Recent empirical evidence on levels of hydrogen knowledge and awareness across society, 2017–2023.

Study	Country context and sample size	Key findings
[31]	Norway (N = 1906)	• Males scored 0.66 points higher on the hydrogen acceptance scale than females (Scale 1–7).
[164]	Australia (N = 2785)	• 65% of male respondents were either 'very supportive' or 'supportive' of domestic hydrogen compared to 40% for female respondents.
[161]	Europe[a] (N = 7148)	• Mean score for awareness of different hydrogen energy technologies (hydrogen fuel cells, residential fuel-cell micro-CHP, and hydrogen fuel cell electric vehicles) across seven European countries = 42.1/100. • Mean score for the UK = 38.7, with a score of 23.0 for residential fuel-cell micro-CHP (M = 25.3 across sample).
[66]	Australia (N = 1824)	• Mean score for knowledge of hydrogen industry (additive index composing of five measures including 'How hydrogen is produced') = 3.22 (Scale 0–10); *SD* = 2.63.
[160]	Australia (N = 2785)	• Mean score for objective hydrogen knowledge = 2.28 (Scale 1–5). • Mean score for subjective hydrogen knowledge score = 1.49 (Scale 1–3).
[179]	United Kingdom (N = 340)	• 23.8%, 40.9%, 28.5%, 4.4% and 1.5% of respondents had not heard about hydrogen before, heard of hydrogen but knew nothing about it, knew a little, knew a fair amount, and knew a great deal, respectively.
[180]	Turkey (N = 964) (N = 415)	• 11%, 45.4% and 35.3% of respondents had not heard about hydrogen, heard about it but had no knowledge, and had little knowledge, respectively. • 81.9% of respondents had little knowledge of hydrogen while 18.1% had some knowledge.

Source: Authors' compilation.
[a] Belgium, France, Germany, Norway, Slovenia, Spain, United Kingdom.

awareness and knowledge has proven low across a range of national contexts. The underlying consensus across empirical studies is that higher educated males are typically the most knowledgeable demographic group, which correlates positively to hydrogen acceptance [126,174,175]. Conversely, consumer scepticism towards HETs has been associated with a lack of knowledge, awareness, and direct experience [82,176]. Both early [124,131,177], and more recent studies [157,160,173,178] report higher levels of hydrogen knowledge and acceptance for males.

An additional observation based on datasets from Europe [124,126,181], and Australia [164,182] is that subjective knowledge of hydrogen has increased over time, which implies positive prospects for social acceptance [78]. Furthermore, statistical results from an Australian nationally representative survey suggest a positive influence of information provision on hydrogen acceptance, equating to a 9% and 11% increase for domestic and export applications, respectively [183].[7] In the South Korean context, Lee et al. [147] also highlight the relative importance of diffusing hydrogen education to support socio-political acceptance for hydrogen buses.

Consumer perspectives on hydrogen production pathways

Regarding production pathways, the literature indicates stronger approval for hydrogen produced from RESs [31,160,179]. For example, a focus groups study conducted with the Welsh public in 2008 revealed stronger approval for carbon neutral hydrogen production methods, with wind farms perceived as a preferable energy source over fossil fuel feedstocks [175]. In the intervening years, studies in the UK [179,184] and international context [160,185] have consistently highlighted public concerns regarding the use of fossil fuels for hydrogen production [159], with overwhelming evidence in favour of renewable-based methods (see Table 2).

Bentsen et al. [31] found that Norwegian citizens held strong approval for green hydrogen (3.90) compared to blue hydrogen (3.20) and grey hydrogen (2.30), as measured on a five-point acceptance scale. The study showed climate change concern to be positively associated with acceptance for green hydrogen [31]. Another Norwegian study provided nuanced insights as to the acceptability of coupling onshore wind with hydrogen production, wherein approval for wind farms (and indirectly support for the green hydrogen sector) increased when priority was given to local decarbonisation efforts (e.g. for municipal transport and industry sectors) [189]. Examining consumer attitudes across five European countries (N = 10,109) which included the UK, Sovacool and colleagues [190] reported lower acceptance rates for hydrogen heating compared to renewable-based alternative such as heat pumps and solar. In the French context, Damette et al. [181] found that consumers were more supportive of hydrogen being converted into electricity off-site and then supplied to households using existing electricity transmission networks (i.e. power-to-gas-to-power), as opposed to gas-based alternatives. Such findings reflect the reality that the policy space around green gas and electrification pathways is often highly contested [184], if not controversial [191]. Notwithstanding, scarce studies have investigated consumer attitudes regarding attributes of different production methods in a specific national context with a publicised strategy [64]. This study seeks to address this knowledge gap in relation to the twin-track approach (blue and green hydrogen pathways), underlying the UK Hydrogen Strategy.

[7] The information package included a short video, followed by images and text descriptions. Hydrogen acceptance also proved context-dependent, with socio-economic characteristics and geographic location having a significant influence [183].

Table 2 – Studies on public perceptions of hydrogen production methods, 2009–2023.

Study	Country context	Methods and sample size	Key findings and comparisons
[186]	United Kingdom	7 in-person focus groups (N = 47)	• Participants opposed the use of non-renewable primary sources to generation hydrogen (foremost nuclear power and coal). • Participants wanted to see more government support for renewable energy-based hydrogen production.
[185]	Germany	Computer-assisted Telephone interview (CATI) survey (N = 1011)	• 66% of respondents expressed a preference for hydrogen produced in an environmentally friendly way (i.e. not via grey hydrogen), even if this increased consumer prices. • 27% of respondents believed hydrogen should be produced from natural gas for a transition period. • 7% had no preference for either option.
[187]	South Korea	Online survey (N = 1000)	• 40% of respondents supported hydrogen produced from nuclear power. • 40% were neutral and 20% were in opposition.
[163]	Australia	9 focus groups (N = 72)	• 74% of survey respondents supported renewable-based hydrogen production. • 54% supported blue hydrogen as a transitional fuel.
[184]	England	Online survey (N = 578)	• Survey respondents preferred green hydrogen (M = 82/100) over blue hydrogen (M = 59/100) as alternatives to natural gas.
[188]	United Kingdom South Wales	Online survey (N = 464) 2 online focus groups (N = 13)	• Participants in both the survey and focus groups reported positive views of green hydrogen (produced via electrolysis), perceiving it as different from the compared technology, namely, fracking.
[179]	United Kingdom	Online survey (N = 340) 5 online focus groups (N = 25)	• 84% of focus groups respondents preferred green hydrogen production over blue or grey options. • Blue hydrogen was perceived as a somewhat acceptable transitional fuel to green hydrogen, while grey hydrogen was perceived negatively.
[160]	Australia	Online survey (N = 2785)	• A mean score of 3.63 (SD = 0.82) for the statement: Hydrogen should be produced using renewable energy and electrolysis only. • A mean score of 3.18 (SD = 0.91) for the statement: Hydrogen should be produced using fossil fuels with CCS as an intermediate step while transitioning to renewables (Scale: 1–5).

Source: Authors' compilation.

Methodology

This section describes the methods of the study, organised according to details of the online focus group approach, recruitment and sampling strategy, topic guide, and data processing techniques composing the mixed methods analysis.

Online focus group approach

Focus groups provide a powerful research tool for supporting the collection of in-depth qualitative data about emerging societal issues [192,193], such as consumer perspectives of low-carbon energy technologies [194–197]. As described by Caporale et al. [198], the focus group approach reveals insights about "participant opinions considering life experiences, expectations, and knowledge about the specific matter to debate." Notably, online focus groups have become a more common research method, especially following COVID-19 [179,199]. The online format offers distinct advantages over in-person focus groups by helping to safeguard against external events,[8] improving overall logistics, and helping to ensure diversity between or within participant groups as per the research requirements [199,200]. However, one notable caveat is that online focus groups exclude demographic groups lacking the necessary means or desire to participate in a digital environment [201]. To carry out this study, 10 semi-structured focus groups were conducted on Zoom between February and April 2022. Each focus group ran for the same duration (~90 min), retained a consistent format, and was led by the same moderator, supported by a co-moderator from Cranfield University's School of Water, Energy and Environment. This approach helped ensure consistency in terms of data collection procedures, information framing, and overall delivery and flow.

Recruitment, sampling strategy and focus group topic guide

Participants were purposively selected through different screening surveys,[9] which filtered respondents into seven distinct categories (see Table 3 and Appendix B).[10] The categories were selected given their relevance to the potential configuration of consumer acceptance for hydrogen homes, whereby a socially acceptable transition [63] will be influenced through a combination of factors: the actions and incentives of early adopters [202,203,203]; engagement from citizens living in industrial areas where the hydrogen switchover is set

[8] For example, two of our focus groups coincided with an extreme weather event in the UK (Storm Eunice).

[9] Qualtrics was used to set-up the screening surveys and to collect the data.

[10] Participants received an incentive in the form of either a cash payment or Amazon voucher.

Table 3 – Details of focus groups, February–April 2022.

Focus Group no., sample size and date[a]	Focus Group category	Location(s) of participants	Recruitment method
FG1 N = 5 February 14, 2022	Moderate interest in renewable energy and joining a renewable energy community (Pilot)	Marston Moretaine, Bedfordshire	Networking with members of the local community
FG2 N = 6 February 17, 2022	Strong interest in renewable energy and joining a renewable community	Marston Moretaine, Bedfordshire	Networking with members of the local community
FG3 N = 3 February 21, 2022	Owners of solar PV panels and multiple smart home technologies[b]	Kilmarnock Portsmouth Torquay	Market research company
FG4 N = 3 February 23, 2022	Actively engaged in environmental issues	Ipswich Leeds Pembrokeshire	Market research company
FG5 N = 5 February 25, 2022	Living in an industrial city or town	Falkirk Flint Liverpool Scunthorpe Yorkshire	Market research company
FG6 N = 3 February 28, 2022	Living in fuel poverty or facing high levels of fuel stress	Cheshire Manchester	Market research company
FG7 N = 6 March 02, 2022	Baseline group (none of the above categories)	Deeside Eastbourne, Hertfordshire Reading	Market research company
FG8 N = 9 April 04, 2022	Actively engaged in environmental issues	Gloucester Kent Stirling Sussex	Social media platforms
FG9 N = 8 April 05, 2022	Owners of solar PV panels and multiple smart home technologies	Lancashire, Lincolnshire London Manchester North Wales	Social media platforms
FG10 N = 10 April 06, 2022	Living in fuel poverty or facing high levels of fuel stress	Isle of Wight Leeds Liverpool London Manchester	Social media platforms

Source: Authors' design.

[a] Due to low participation in some of the initial focus groups (FG3, FG4 and FG6), the research team opted to organize three additional focus groups to secure larger sample sizes for the affected categories.

[b] Smart lock, video doorbells, smart thermostat, smart alarms, smart camera, smart speakers, smart bulbs, smart plugs, smart kitchen appliances, smart light switches, robot hoovers, smart blinds, smart smoke detectors, smart TVs, garage door openers, universal robots.

to commence [204–206]; public attitudes towards hydrogen as a net-zero fuel [207,208]; and impacts on fuel poverty and fuel stress [209–211]. As a control measure, a 'Baseline Group' (FG7) was included in the analysis, which filtered out the specifications of other focus groups, thereby providing an additional measure for comparative analysis.

Supporting the research design, we applied quotas in Qualtrics (i.e. for age, gender, and location) to help target a nationally representative sample where feasible (see Appendix B). Critically, the sample included a near equal balance of male and female respondents (N = 31, N = 27). Residents from Marston Moretaine (nearby to Cranfield University) were recruited for the pilot focus group (FG1), wherein participants had a moderate level of interest in renewable energy and in joining a renewable energy community. Thereafter, participants in the second group (FG2) expressed a stronger interest regarding renewable energy, and were also regular visitors to the Marston Vale Forest Centre, which engages in climate protection [212,213] and is partly powered by a wind turbine [214]. Results from FG1 met all requirements for subsequent data analysis, which supported the suitability of the focus group format and content.

Following prior literature review on the subject matter [63,78], the research team developed a topic guide to stimulate discussion across a range of areas connected to the hydrogen transition (see Table 4). Additionally, participants received two basic types of information provision (i.e. PowerPoint slides and videos) to enable a more meaningful discussion on hydrogen (see Fig. 1). Enhancing the data collection protocol,

Table 4 – Focus Group format.

Topic Guide category	Topic description
Introduction	
C1	• Cooking technologies and consumer preferences
C2	• Heating technologies and consumer preferences
C3	• Climate change, the environment, and renewable/low-carbon energy technologies
C4	• Knowledge and awareness of hydrogen (general) and preferences for reliable sources of information
RQ1	
Information provision round 1	
RQ2	• **Poll 1 and discussion:** Consumer views on the UK's twin-track Hydrogen Strategy
Information provision round 2	
C5	• Trust in key actors and stakeholders of the hydrogen transition
	• *Information provision round 3*
C6	• Community benefits, costs, and risks of hydrogen
C6	• Individual impacts and disruption related to the domestic hydrogen switchover
C7	• Choice of energy suppliers, appliance brands, and models for domestic heating and cooking
C8	• Costs of hydrogen appliances (purchase, running, and maintenance)
	• **Poll 2 and discussion:** Willingness to switch to hydrogen appliances and to live in a hydrogen home
RQ2	• **Poll 3 and discussion:** Consumer preferences for hydrogen in the UK's energy future
C9	• Key messages for actors and stakeholders shaping the hydrogen transition
	• Conclusion
Description of information provision	
Round 1	• PowerPoint slides on hydrogen production and the UK's 'twin-track' hydrogen strategy
	• Video on the UK Hydrogen Strategy https://www.youtube.com/watch?v=g-VpyglBhrI&t=32s
Round 2	• Video on the H21 Project https://www.youtube.com/watch?v=CtAzCv5Sc48
	• PowerPoint slide on the key actor-networks composing the UK domestic hydrogen landscape
Round 3	• PowerPoint slide on the spatial dynamics of the UK domestic hydrogen transition
Description of polls	
Poll 1: RQ1	• Consumer views on the UK's hydrogen strategy and the twin-track approach
Poll 2	• Willingness to switch to hydrogen appliances and to live in a hydrogen home
Poll 3: RQ2	• Consumer preferences for domestic hydrogen in the UK's energy future

each focus group was supported by three poll questions. In line with the specified research questions, this study reports the results from Poll 1 and Poll 3.

Mixed methods data analysis

Mixed methods research (MMR) provides a robust means for grappling with the multi-dimensionality and complexity of social issues, while enhancing the discoverability of patterns in retrieved data [216], as compared to studying qualitative and quantitative outputs in isolation [217,218]. While traditional MMR designs include a separate qualitative and quantitative phase [218,219], mixed methods data analysis can also be presented within a single method [220]. For example, Vogl [216] integrated qualitative and quantitative results from a focus groups study, and derived findings from the interactions between these two strands (i.e. meta-inferences). Thus, 'mixed analyses' can be considered as a specific variant of MMR, wherein a single round of data collection is analysed through qualitative and quantitative strands [216]. Integration brings the respective data strands into conversation with one another [218], serving to enhance the richness and explanatory power of conclusions [221].

As a focus groups study, this analysis follows a separative approach whereby the qualitative and quantitative data analyses are carried out independently of one another, before meta-inferences are drawn through interpreting and reporting the implications of the integrated findings through narrative weaving [222]. This study is qualitatively driven for all research questions (i.e. qualitative: participant statements → quantitative: poll results), which adheres to the temporal relation of the data collection [219]: polls were employed following discussion between focus group participants, as a way of further quantifying and validating their perspectives on hydrogen.

For the qualitative strand, this study applied a combination of thematic and content analysis [223], which is consistent with the approach of Smith et al. [179] in their study hydrogen perceptions in the UK context. Adhering to established protocols [77,196,224,225], the audio recordings were transcribed and inductively coded verbatim in NVivo12 [226], thus, preserving the entirety of the recorded data [227]. Thematic analysis [228] was undertaken to detect and identify patterns in consumer responses, and areas of convergence and divergence in opinions [229].

Reflecting the mixed-methods nature of this study [230,231] (see Fig. 2), the analysis includes a series of summary tables and figures, alongside illustrative quotations which capture the voice of participants and the narratives put forward [77,219,232]. Subsequently, content analysis provides a means for systematically organising and quantifying participant statements according to each theme (code) and sub-theme (sub-code) [233]. For the quantitative strand derived from poll data, statistical analyses were conducted in SPSS 27.0 to examine differences across the sample and between groups. Finally, data integration at the level of reporting key findings relies on narrative weaving [179,221], as a means for structuring the discussion and deriving meta-inferences [234].

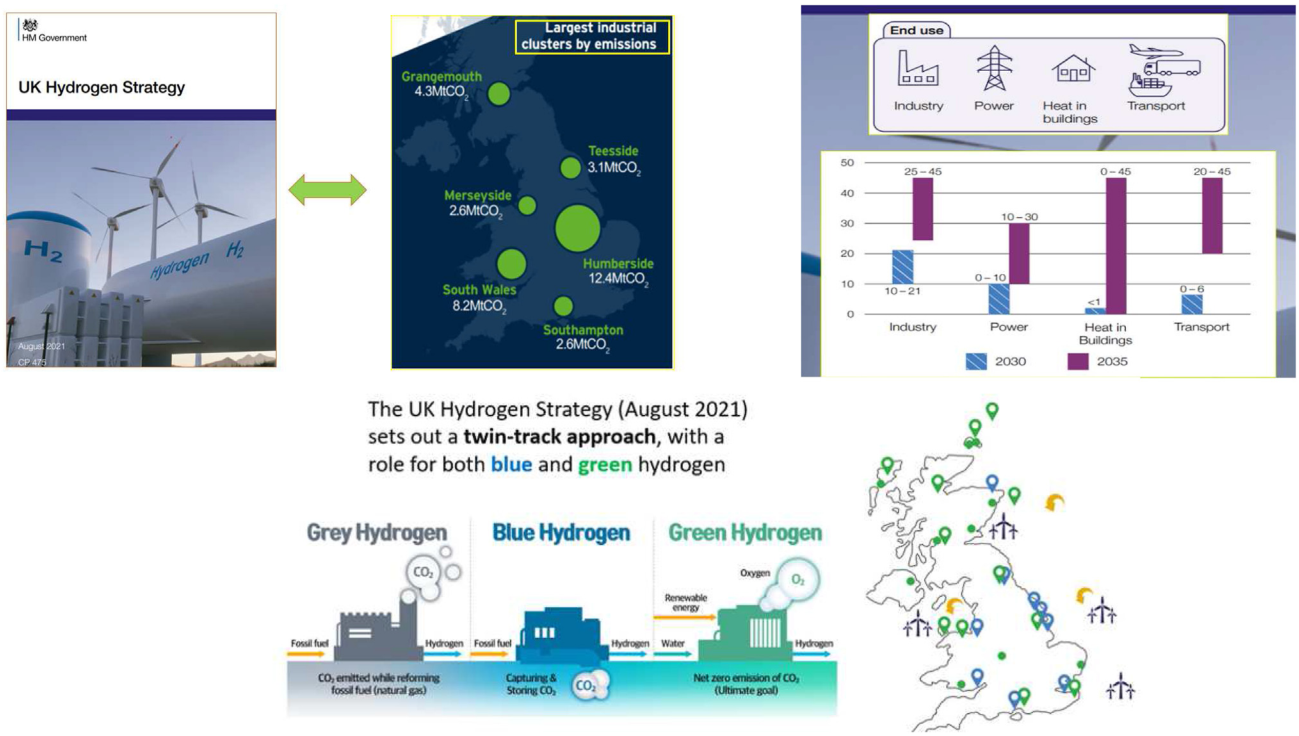

Fig. 1 – PowerPoint materials. Panel A highlights links between UK industrial strategy and the Hydrogen Strategy. Panel B shows demand projections (TWh) for UK hydrogen. Panel C contextualises hydrogen production and outlines the twin-track approach. Source: Author's design based on [46,55,215].

Results

This section reports results on hydrogen knowledge and awareness (see Section Measuring hydrogen knowledge and awareness), consumer perceptions of the twin-track production approach (see Section Consumer perceptions of the twin-track approach), and perceptions of domestic hydrogen futures (see Section Public perceptions of hydrogen futures). The section closes by unpacking consumer preferences for information dissemination on hydrogen home appliances and the domestic hydrogen switchover.

Measuring hydrogen knowledge and awareness

Prior to the moderator announcing the main purpose of the focus group, some details about hydrogen were raised spontaneously in several focus groups, with 26 individual responses recorded across the sample. Once formally introduced as the main topic of interest, participants were asked directly whether they had heard of hydrogen before and in what context, and to what degree. Accordingly, results on this aspect were provided through direct observation and validated during the subsequent analysis of transcripts. Reflecting on the findings, hydrogen knowledge and awareness was measured according to four distinct categories (see Table 5).

Participants with moderate to high knowledge and awareness of hydrogen

Across the sample, only five participants (FG2:2, FG3:1, FG8:2, FG8:3, FG9:2) proved knowledgeable about hydrogen and were informed about its potential use in homes. All participants in this category were males, aged between early-30s to mid-70s. This finding is consistent with the literature, which reports a prevalence of greater hydrogen knowledge levels among educated males [126,160,161]. Additionally, the respondents in this group had teaching or engineering backgrounds. Foremost, the technical risks and constraints of hydrogen were flagged, with a focus on safety and production concerns.

Regarding the risks of hydrogen, one participant responded "*… it can be dangerous, but then again so is gas and electricity … it's about handling it correctly*" (FG2:2). On the topic of electrolytic hydrogen, he expected "*things to go in that direction,*" but worried about production costs and risks of electricity sources not being green (FG2:2). Another participant described the need to scale up domestic renewable energy capacity to support clean hydrogen production and cited storage and transportation as "*obvious problems,*" while also acknowledging "*safety concerns due to the very nature of hydrogen*" (FG3:1). Reflecting on the broader discussion between hydrogen and electrification, one respondent believed commitment to either pathway presented a risk of "*being locked into that technology for maybe 10, 20, or 30 years,*" which he considered an unacceptable risk (FG8:2). Demonstrating the relevance of location, a participant from Teesside explained how some of the chemical manufacturers in the area are "*looking to develop hydrogen facilities to pipe it into the mains*" (FG8:3), in conjunction with the South Bank project [235].

Finally, a participant with solar panels and smart home technologies (FG9:2) believed "*it would be much better if they*

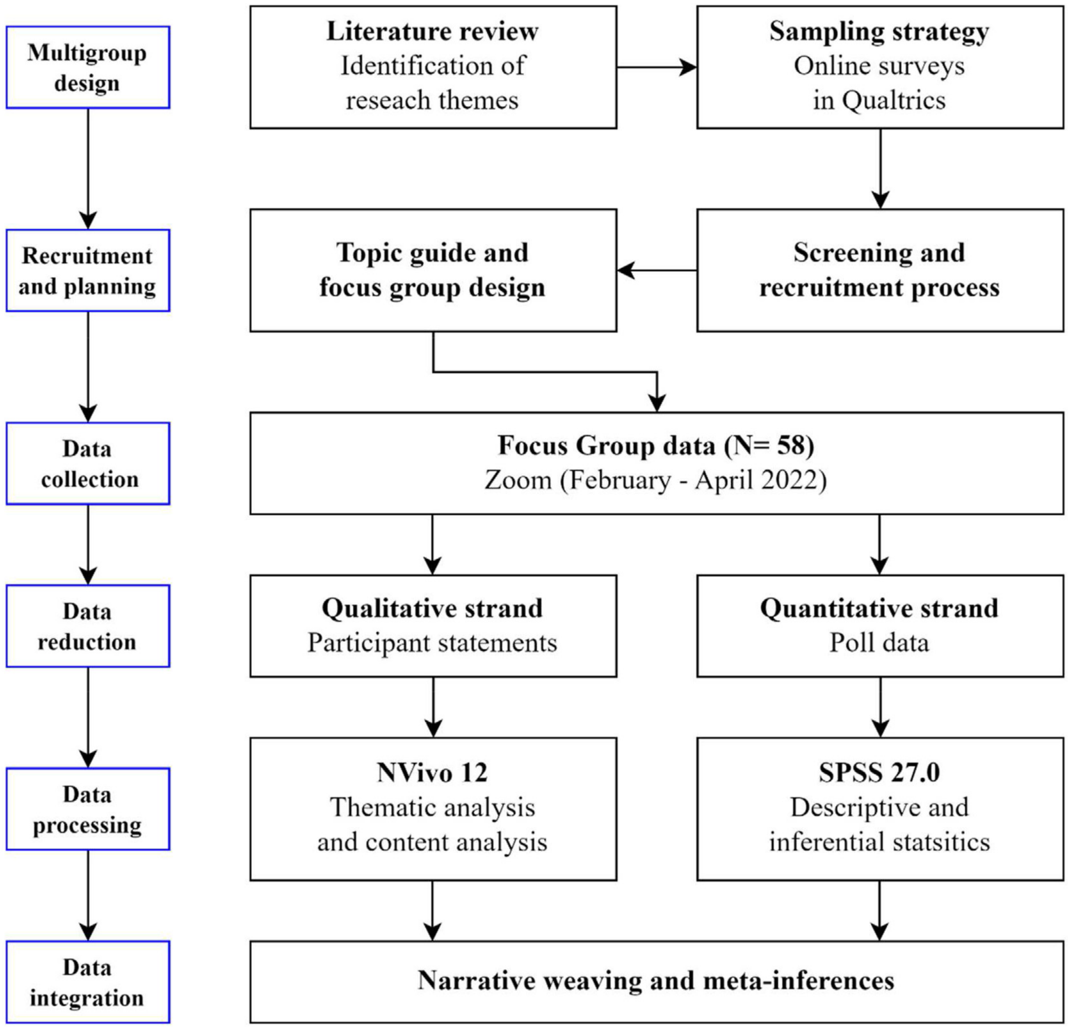

Fig. 2 – Sequential overview of research design and methods.

Table 5 – Definition and distribution of hydrogen knowledge and awareness levels in this study.

	Definition of knowledge and awareness category	Number of responses (%)
Low	• No real knowledge of hydrogen and only familiar with it by name alone	32 (55.2)
Limited	• Some knowledge and awareness of hydrogen which remains limited to basic understanding or familiarity	11 (19.0)
Some	• Ability to contextualise some examples of hydrogen applications and demonstrate basic knowledge	10 (17.2)
Moderate to high	• Familiar with hydrogen to at least a moderate level with ability to demonstrate more than basic understanding	5 (8.6)

could pipe hydrogen into houses instead of natural gas, like in Orkney" [236]. In addition to mentioning concerns about hydrogen storage, its pressure and volatility, the same respondent explained that "*… you'd need 5 kW of electricity to bubble off 1 kW of useable hydrogen, so it's absolutely fine if the grid overflows … then you could in theory dump that energy into creating hydrogen.*" While acknowledging that a lot of the infrastructure may be in place for hydrogen, he concluded that "*it's never going to be a cost-effective solution until we get ten times more renewable electricity generation*" (FG9:2).

Participants with some knowledge and awareness of hydrogen

Ten participants, spread across half of the focus groups (FG1:4, FG1:5, FG2:3. FG2:5, FG3:2, FG5:1, FG5:3, FG9:1, FG9:3, FG9:8), demonstrated some relevant knowledge of hydrogen and were able to mention a few specific applications (see Appendix C). In this case, the distribution was evenly split between male and female respondents. On the more negative side, one participant warned of hydrogen's "*high volatility, which would make some people think twice, or even thrice about it*" (FG9:8). Another respondent anticipated "*huge safety issues* *with hydrogen*" and raised concern around storage problems and the practicalities of piping it into homes (FG5:3). Two participants had some direct experience with hydrogen-ready boilers and demonstration projects. One respondent shared concern about the fuel being "*quite dangerous*" (FG2:5), while the other mentioned their recent experience with Gas Distribution Network Operator (GDNO), Cadent Gas, carrying out the Iron Mains Replacement Programme in their local area [237,238], with the promise of "*... hydrogen becoming a possibility in the future, that's what they've told us*" (FG9:1). Other participants were mostly familiar with hydrogen fuel cell vehicles (FG4:1, FG2:3).

Participants with limited or no knowledge and awareness of hydrogen

Nearly three-quarters of participants had less than some knowledge and awareness of hydrogen, with most of this subgroup (~74%) having no knowledge of hydrogen and familiarity only by way of name. Of note, the fuel poor group was composed of 85% having no knowledge and 15% having limited knowledge and awareness. Among older participants, familiarity with hydrogen was limited and could be traced back to high school science class. One participant acknowledged how any associations with hydrogen stretch back to their "*chemistry days*" (FG3:1) which drew agreement from fellow participants (FG3:2, FG3:3). Another respondent also reflected on their chemistry class days:

> *I would have thought most people are not really sure what it is, unless you remember being in the chemistry lab. I would have probably known if I was 16, but perhaps don't know much now* (FG5:4).

Conversely, and highlighting generational implications around hydrogen engagement, one respondent explained how their teenage son had recently mentioned that "*hydrogen could be big for the future*" (FG7:6). Among participants with a slightly higher awareness level of hydrogen, familiarity was typically linked to hydrogen for transport applications and the source of this knowledge was usually news coverage (see Appendix C). These observations broadly align with recent findings in the UK context, which suggest secondary school education, news coverage, television shows, and internet sites configure one's social representation of hydrogen and corresponding knowledge level [179].

Knowledge and awareness levels across focus groups and between genders

The results support empirical evidence in the literature which suggest males are more likely to be classified as highly knowledgeable on this topic (see Fig. 3). Males received a mean score of 2.00 compared to 1.56 for females,[11] which was explained by five male respondents demonstrating a moderate to high level of hydrogen knowledge and awareness (see Appendix D). However, across all other levels, there was no discernible differences between genders. By contrast, Smith et al. [179] reported that female respondents had a subjective knowledge level falling between "I have not heard about it before" to "I have heard of it but know nothing about it," whereas male respondents ranged one level higher, between "I have heard of it but know nothing about it" to "I know a little." However, it should be noted that the sample distribution in the aforementioned study [179] was somewhat unbalanced, with 61.2% female respondents, compared to 46.6% in this study. Otherwise, gender differences had little impact on hydrogen perceptions in our study (see Appendix D). Any provisional findings should be verified by larger and more representative UK survey studies, while the generalisability of results should be tested through cross-country comparative studies.

To investigate potential differences in levels of knowledge and awareness, the mean score for each of the seven groups was calculated and compared to results across the sample ($M = 1.79$) and groups ($M = 1.87$). This procedure showed that knowledge and awareness of hydrogen is positively associated with interest and engagement with RETs (FG2: $M = 2.50$; FG3 and FG9: $M = 2.30$), whereas participants facing fuel poverty appear to be the least informed group ($M = 1.15$). Interestingly, respondents engaged in environmental issues had a below average level of hydrogen knowledge and awareness in this study, which was contrary to expectations ($M = 1.67$). A probable explanation for some of the observed variance in knowledge and awareness levels ($SD = 0.46$) is age gaps between certain groups (see Appendix E), however, detailed analysis of socio-demographic variables is beyond the scope of this exploratory, small-sample study.

Access to sources of reliable information on hydrogen

Following the initial assessment of hydrogen knowledge and awareness, participants were asked how they would access reliable information about hydrogen in the future. Respondents typically focused on internet sources, which included Googling for "*decent scientific sites*" (FG2:2) such as Scientific America (FG3:1) and other "*trusted sites*" (FG8:6). Some respondents suggested searching relevant online forums to "*see what people are saying*" and to "*hear people tell their story*" (FG5:5). Two professionals mentioned specific options such as the Institution of Engineering and Technology (FG2:2) and the Buildings Services Research and Information Association (FG2:5). One participant also suggested looking to see "*what local councils are doing on their websites*" (FG8:6), while another recommended finding "*someone who already has one of these systems in their house or has taken part in a trial to see how they fared with it*" (FG5:2).

Along similar lines, a participant engaged in environmental issues explained how they "*would probably Google and try to find accurate information, hopefully which is backed by evidence too*" and "*also look at what the local council says*" (FG8:9). In the eyes of one respondent, the sources should be from trusted departments including "*government websites and the office of national statistics, which promote and spread knowledge to the people*" (FG10:2). Following this comment, another participant offered an alternative approach, "*I'd try to access information from my energy provider; they might be the right ones to get the information from*" (FG10:3).

[11] Lowest knowledge and awareness = 1; Limited knowledge and awareness = 2; Some knowledge and awareness = 3; Higher knowledge and awareness = 4.

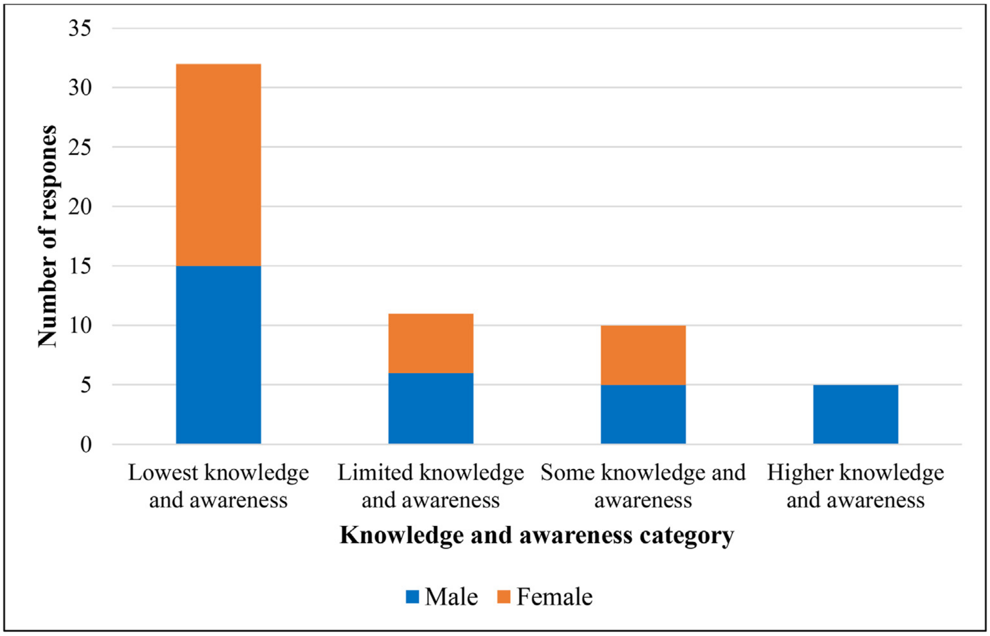

Fig. 3 – Breakdown of knowledge and awareness levels across focus group sample by gender.

Across the sample, the most cited sources for accessing reliable information on hydrogen included scientific websites, government websites, professional online platforms, local councils, and energy providers. In sum, government, media, energy providers, professional institutes, and local councils have a clear role to play in disseminating clear and meaningful information to the public. At the same time, there will be different preferences and tendencies across parts of the public when it comes to deciding which platforms to access and trust. For a growing part of the population, internet sites are likely to be the most immediate source of information. However, the activities of local councils may prove critical to spreading information about hydrogen in a more direct and impactful way at the grassroots level [239].

Consumer perceptions of the twin-track approach

Following the first round of information provision (see Table 4), participants were presented with a follow-up poll question: *How do you feel about the government's twin-track approach? (with a role for both blue and green hydrogen production)*. As the focus groups were conducted prior to the announcement of the British Energy Security Strategy in April 2022, participants understood that both production pathways would be implemented, however, there was no specific guideline was communicated regarding the potential share of blue and green hydrogen production.

Responses were measured on a five-point Likert scale, ranging from (1) *very opposed* to (5) *very supportive*. 93% of participants completed the poll (N = 54), with one-third positioning themselves as *very supportive* of the twin-track strategy. The most frequent position was *somewhat supportive* (N = 24), which accounted for nearly 45% of the responses. Of the remaining responses, participants were *somewhat opposed* (N = 5), followed by *neutral* (N = 4), while only one respondent proved *very opposed*. The next sections review the explanations given by respondents for these respective positions.

Positive perceptions of the twin-track approach

Positive views of the twin-track approach stemmed from seeing it as a "*logical*" choice and "*calculated decision*" (FG9:2), which may help maintain convenience for end-users, while minimising disruption (FG5:2, FG6:3). This was viewed as a "*welcome development*" (FG9:5) and "*good news*" (FG4:2), wherein the government was seen to be "*taking the initiative*" (FG9:2) to address climate change (FG3:2, FG4:1, FG4:3, FG10:2, FG10:4). One participant concluded that "*it makes perfect sense they would target heavy industry first and might rely on blue, but eventually look to go all green*" (FG3:3).

Other positive perceptions, albeit with more moderate levels of support, were formed around seeing the twin-track strategy as aligned to potential energy security benefits and cost reductions to consumer bills (see Appendix F). For example, a Scottish participant saw it as "*positive news and a step in the right direction, if they're going to be getting away from grey hydrogen*" (FG5:5). However, several participants highlighted the need to understand a lot more about both cost and environmental impacts, either requesting or demanding more information to consolidate or strengthen their support. In the words of one respondent, what matters most is "*how cheap it will be for the average person, at the end of the day*" (FG7:1).

Despite some consensus that the twin-track approach may prove a more full-proof strategy for deploying hydrogen, there was underlying scepticism about the benefits of doubling down on a blue hydrogen production pathway to help reach net zero [62]. For example, one respondent inquired about "… *how fast would the transition go, from grey to blue to green; what's the timescale to eventually being totally green, if possible?*" (FG3:2). Although several participants declared themselves to be *somewhat supportive* when answering the poll, upon further inspection (i.e. probing from the moderator) this positivity was often contingent on the Hydrogen Strategy supporting environmental benefits and cost savings to consumers. Conservatively, it may be concluded that positive perceptions of the twin-track approach were somewhat inflated in the poll results compared to articulated responses, which leaned more towards neutral, but otherwise hopeful perceptions. In response, subsequent research could employ a seven-point Likert scale to better differentiate response patterns.[12]

Neutral perceptions of the twin-track approach

Participants who were more neutral or undecided about the merits of the Hydrogen Strategy felt that the twin-track approach was indecisive; referring to it as "*half-hearted*" (FG8:3, FG9:1), "*half-baked*" or a "*half-way house*" (FG3:1) One participant associated the strategy with the shortcomings of transitioning to electric vehicles, "*... if they are really going to invest in it, they have got to do it fully ... it's like with electric cars, they've only done it half-way*" (FG2:3). This response was especially noteworthy since the respondent was *somewhat supportive*, as opposed to neutral or opposed to the twin-track approach. Such framings underscore the need for the government to pre-empt consumer resistance on environmental grounds – or due to negative association with past policy failures such as diesel cars [240] or the Green Deal [241] – by justifying the legitimacy of committing to a blue hydrogen pathway. Another participant expressed scepticism over the legitimacy of community benefits promised by the hydrogen transition:

> *The twin-track approach seems like a half-hearted situation and from experience of what I'm seeing here in Teesside, it's the opportunities that the business world and the private sector see for their own benefit rather than from an environmental point of view. I sound very anti-capitalist, but that's not the point. It just seems that investment goes into something and then ends up in someone else's private pocket* (FG8:3).

Additionally, some participants were concerned about heightened risks to early adopters, the profit motives of private companies, and the need to address a vast array of 'unknown' factors (see Table 6).

Negative perceptions of the twin-track approach

Participants *somewhat opposed* to the strategy objected more strongly to the use of fossil fuels, viewing hydrogen as potentially wasteful compared to using electricity directly from the grid. Red flags were also raised regarding safety concerns and mistrust in the government (see Table 6). In terms of safety perspectives, consumers worried about the explosive risks of hydrogen and the suitability of an orange flame, as opposed to the familiar blue flame (FG1:4, FG7:1, FG9:3). One respondent also admitted to being unsure about "*getting on a plane that's fuelled by hydrogen*" (FG7:6), reinforcing how public perceptions of other end-uses such as transport applications may impact the social acceptance of domestic hydrogen.

Only one participant (FG8:1) was *very opposed* to the UK Hydrogen Strategy in general, based on ideological grounds rather than an assessment of the twin-track approach per se. In their view, the short video – which featured statements from the Head of hydrogen projects, Northern Gas Networks (Tim Harwood), former UK Business and Energy Secretary (Kwasi Kwarteng) and a Chief Scientist from Greenpeace (Dr. Doug Parr) – was judged to be "*very big brother*" and one-sided, representing "*all men ... telling you what to do*" (FG8:1). This respondent shared an important perspective which resonates with the notion of internalising distributive, procedural and recognition justice [242] into the decarbonisation agenda, as a prerequisite for facilitating social acceptance [243,244]:

> *If you are going to change things, people need to be brought along for the ride and educated. They need to be bought in, to love and be included in it ... the fundamental element of change is you have to bring people along and if you don't demonstrate diversity and you don't include people, then you've lost 80% of your audience without even trying* (FG8:1).

This commentary received degrees of acknowledgment and approval from some members of the focus group. Notably, public participation, established on foundations of deliberation and inclusion [245], has been linked to mobilising an accelerated and just energy transition [246–248], which the above statement attests to.

Perceptions of the twin-track approach across focus groups

Given that 78% of respondents expressed underlying support for the twin-track approach, split between 39% *very supportive* and 46% *somewhat* supportive, there was minimal quantitative data representing neutral or negative perceptions. Notwithstanding, some notable patterns emerged when analysing the poll results in relation to focus group categories (see Fig. 4).

Differences in consumer attitudes towards the twin-track approach were measured by calculating the mean score for each group (Scale 1–5: Very opposed – Very supportive), as described in Appendix F. Foremost, citizens living in fuel poverty or facing high levels of fuel stress ($M = 4.67$), and owners of solar PV panels and smart home technologies ($M = 4.55$) expressed the strongest level of support for the twin-track approach. For the former group, hydrogen was largely welcomed, with hopeful visions for improving the environment and lowering energy costs in the long-term. The latter group perceived a scaling up of hydrogen production – whether blue or green – as a positive step towards advancing the net-zero agenda.

Next, citizens living in industrial towns expressed the strongest level of support for the twin-track approach ($M = 4.40$), perceiving hydrogen as a stimulus for reinvigorating industrial areas and delivering economic growth, as well as local jobs. Convergence between participants experiencing fuel poverty and those living in industrial towns may be explained by the fact that several fuel poor respondents were from large cities in Northern England, namely, Manchester ($N = 6$), Leeds ($N = 1$) and Liverpool ($N = 1$).

[12] In this study, a five-point Likert scale was deliberately chosen to help maximise responses rates and for efficiency purposes (i.e. minimising time spent on the polls to enable richer discussion).

Table 6 – Critical concerns and reservations regarding the twin-track approach.

Participant	Position	Illustrative quotations
FG1:2	Somewhat opposed	• *I'm somewhat opposed to this idea of a two-track system. Why can't we just go for the green? I don't understand why we have to do the blue and green? If green is the best option, why are we somewhere in the middle?*
FG1:5	Somewhat opposed	• *Why don't we just go with the best environmental option? I understand that there's a cost difference … but I think for me it's about trusting the government, that they will do right by us and by the planet. And I don't quite trust what they'll do because they'll always have another agenda that's trying to be achieved, other than looking after us and the planet. So, that's why I'm somewhat opposed, but I might feel that way about anything the government comes up with.*
FG3:1	Neutral	• *… well, the mix is a half-way house, and it needs to eventually be transmitted to fully green! But it makes sense the hydrogen strategy. It's logical that industry is the primary use … a transition period where the boilers are made to run on both, that's critical. It has to happen.*
FG7:5	Somewhat opposed	• *I was opposed to the twin-track approach because I don't see the point. Why not go straight for the green, if you're going to do it?*
FG8:2	Somewhat opposed	• *It's still burning stuff though, isn't it, unfortunately. And that's what we're trying to avoid … it's still burning stuff and it doesn't matter what spin you put on it. In some parts of the country, there is no green … it's a fudge like E10 fuel … like buying diesel cars in 2009. CCS is sweeping what we burnt under the carpet.*
FG9:1	Somewhat opposed	• *I wouldn't be happy to move into something which is half-hearted … I think more needs to be done to move towards a more environmentally solution. I think it's crazy when you've got solar power and wind and you're using that power to generate hydrogen. So, it doesn't seem feasible to me, and it does worry me about it being piped into my property. I just feel that it's using large amounts of electricity and still using fossil fuels … I don't see the point. I just don't feel it's the way to go, especially with the blue hydrogen.*
FG9:3	Neutral	• *I was kind of on the fence. I'm not used to the orange flame. Would that pollute? What are the risks there? The price will be high at first but then might come down, so will the early adopters or first testers be like the scapegoats?*

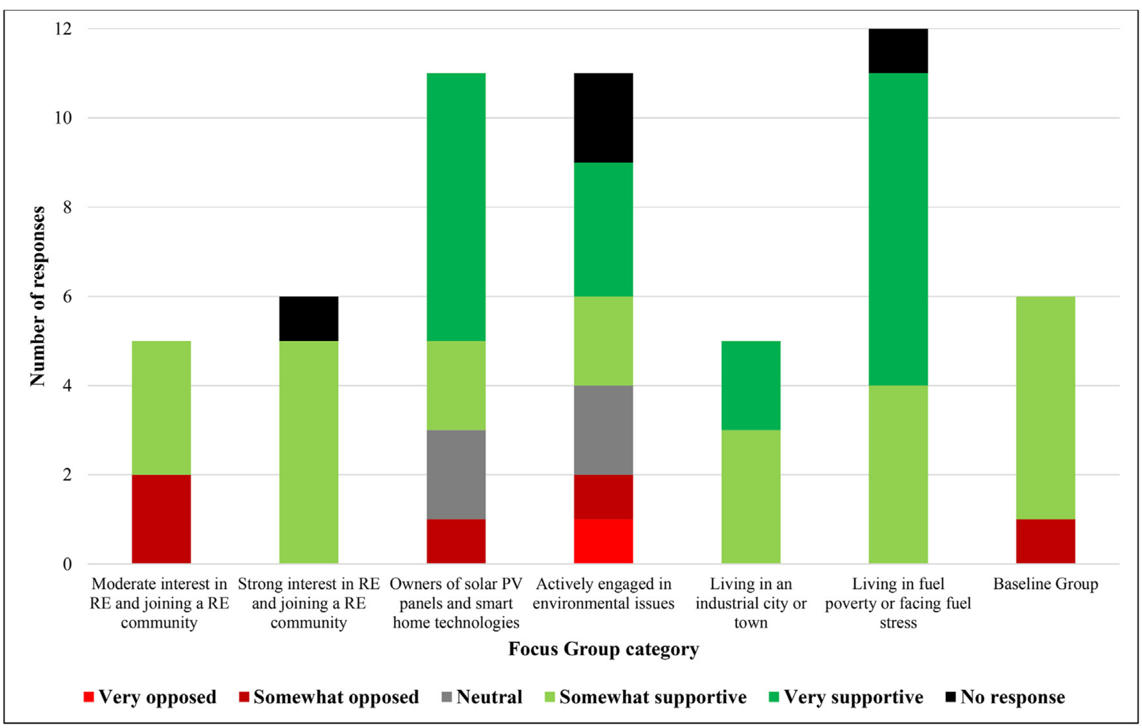

Fig. 4 – Consumer attitudes towards the twin-track approach across focus groups.

Divergence in opinion was observed between the two groups from Marston Moretaine, Bedfordshire, with the more renewably engaged group expressing stronger support for the twin-track approach ($M = 4.00$). This discrepancy fits with expectations and suggests that familiarity with onshore wind farms and solar PV, and environmental protection may bolster the potential for hydrogen acceptance. Additionally, it is noteworthy that participants actively engaged with environmental issues presented the widest range of responses and, by comparison, the lowest levels of *very supportive* or *somewhat supportive* positions (60% of responses compared to a mean of 85% across the sample).[13]

Tellingly, neutral and negative perceptions were largely attributed to scepticism or disapproval concerning the inclusion of blue hydrogen as a decarbonisation pathway.

[13] The Pilot group (FG1) also recorded 60% for this answer category.

Notwithstanding, the environmentally engaged group shared a similar level of overall support for the twin-track approach as the baseline group ($M = 3.70$). While these findings remain exploratory due to the limited sample size, there is clear strategic value in seeing whether these results can be validated, or possibly become more pronounced in some ways when dealing with a larger dataset.

Public perceptions of hydrogen futures

Near the end of the focus group, participants were asked to complete a final poll question, for which the response rate was 100%: *Overall, how do you feel about hydrogen homes being part of the UK's energy future?* Alongside the poll data, several respondents justified the rationale behind their viewpoints (see Appendix G). This section systematically reviews consumer perspectives on this scenario according to key themes and concludes by comparing results across focus group categories.

Environmental benefits and intergenerational climate justice

The main driver of support for domestic hydrogen futures across the sample was recognition of potential environmental benefits, which were described by members of one focus group as the need "*to go greener*" (FG1:1), "*… take us a step closer to being carbon neutral*" (FG1:2) and "*make a big difference to climate change*" (FG1:3). Elsewhere hydrogen was viewed as "*the way forward to get carbon neutral and sustainable*" (FG4:2) and an effective means for discontinuing "*the carbon intensive lifestyle we've been used to.*" (FG9:6). Among owners of solar panels and smart home technologies, support stemmed from the environmental promise of hydrogen, and moreover, green hydrogen. The theme of intergenerational climate justice was also discussed, with one respondent calling hydrogen "*a step in the right direction*" and describing themselves as "*ready for a change*" to "*something much more sustainable and safer for the environment, for the generations to come*" (FG9:3). Similarly, a fuel poor respondent saw hydrogen as an "*opportunity to do something better for the planet … not just our generation, but future generations*" (FG6:2). Such remarks were greeted with approval by fellow participants.

Disruptive impacts and energy efficiency

In addition to environmental benefits, positive responses to hydrogen centred on its perceived potential in minimising the disruptive impacts of residential decarbonisation, while promoting efficiency gains for household heating. These arguments align closely to what advocates typically cite as the main advantages of hydrogen, compared to alternative technologies such as heat pumps [249,250]. This sense of technology optimism (see Table 7) reflects a scenario in which low-carbon hydrogen appliances provide a like-for-like replacement existing boilers and hobs, thereby minimising disruption to the consumer [249–251].

Cost concerns, risk factors and information deficits

Reservations concerning domestic hydrogen stemmed mainly from the desire to know more about the personal impacts of the switchover (see Table 8). However, an underlying information deficit often translated into greater perceived risks. A fuel poor participant expressed concerns over the "*unknowns*" of cost factors as well safety aspects, asking for greater clarity on these areas (FG6:1), while a fellow respondent stressed the need for transparency on cost factors (FG6:2). Similarly, the initial response in Focus Group 9 cited the need for "*more information on cost, disruption, and safety*" (FG9:1). In several cases, environmental concerns were trumped by financial concerns, which emerged as common theme across focus groups:

> *Although I am concerned about the environment, I hate to say it, but I am most concerned about myself and my family. So, it's all about how it affects me really, and would it be worth my while and how much might I potentially save* (FG3:3).

This finding is consistent with the Schwartz's theory of value contents and structure [252,253], wherein hedonic values such as personal comfort and financial security outweigh more self-transcendent or collective values linked to environmental protection and intergenerational climate justice [254]. In the words of one respondent, "*… even though I want to make a positive change, I don't want to do it at a big cost to me*" (FG6:2).

Table 7 – Positive expectations for minimising disruption and maximising energy efficiency.

Participant	Illustrative quotations
FG1:4	• *Whenever we've had a new gas boiler at home in the past, we've found it to be much more efficient than the old one. I would be hoping hydrogen would be as efficient or more efficient than what it replaces.*
FG2:1	• *… it will operate the same as the gas does, then to me you don't need to have your house tore apart.*
FG2:3	• *… because if you're trying to get people to adopt a brand new technology that's completely alien to them, most people won't do it. It will take years for that to happen, whereas this is fairly normal, with minimal pain or disruption. If there's a technology that allows us stick with the bulk of what we have: we don't need to change our radiators, we don't need to learn to cook differently, we don't need to put new pipes in; all we need to do is switch out a boiler and switch out a hob essentially.*
FG5:3	• *It's opened my eyes this forum tonight and especially the [second] video. That house looked pretty normal. I don't know what I expected like a big tanker outside maybe or a cannister or something, but it didn't look intrusive. So, I'm feeling a lot more positive about it than I probably was before.*
FG7:6	• *I've heard about heat pumps, but this seems quite straightforward in a way. You are replacing gas with hydrogen coming through the pipelines and that's why I'm supportive of it. I understand it a lot more than I do heat pumps. Although there might be a short-term disruption, you haven't got a big thing hanging on your wall like a heat pump. So, you wouldn't really notice a difference.*

Table 8 – Reservations concerning the proposition of hydrogen homes.

Participant	Illustrative quotations
FG1:3	• *I'm somewhat supportive but before I could be fully on board, I would need to know a lot more about it.*
FG5:1	• *For me, it's all about hearing from real people who are part of the trials and how they lived day-to-day with their family using hydrogen, so they can feed back to us and give us an honest view of what it's like moving over to that new system. For me, that is the one thing that would convince me to change.*
FG5:3	• *Teething problems like safety issues that might be encountered once this in place and people have real life experiences.*
FG5:4	• *We all need more education on it and that's what the videos helped with, but probably we still need to know a lot more about it.*
FG5:5	• *Yeah, the concept is good … see how the trial goes like and how it rolls out, but sure, cost is the main factor.*
FG6:2	• *I think lack of information is probably the big thing that hinders me from saying I'm extremely willing; lack of information on price … most questions will be around the finance of it because that's where we're out of pocket to begin with.*
FG6:3	• *You would need to know a lot more information. For example, if you provided a sheet that said these were the costs here, that would make my mind up about how supportive I am … it's the cost that would be the main factor for myself. The costs and also the safety aspects of it all, is it safe.*

Energy injustice and trust deficits

Among environmentally engaged participants, two respondents (FG8:2, FG8:3) perceived hydrogen futures through a neutral lens. Notwithstanding, the critique of one participant suggested a degree of resistance based on a view of systemic injustice within the UK energy system:

> *Energy shouldn't be for-profit … how can you make profit from people's suffering? The environment is suffering, and the usual suspects are profiteering at the end of the day, and that seems to be a big problem … and how do you basically change the model so it does become more like the NHS … it's centrally funded and it has those values as its core principles … I'll pay for it when I'm comfortable that I've been able to make the right decision … that's why I've turned down previous grants that were free* (FG8:3).

Additionally, the same respondent relayed personal experience of rejecting government grants for home retrofits based on professional knowledge of the trade. Specifically, grants were regarded as flawed and inadequate, since choices are ultimately taken by the installer, which may discriminate against low-income households:

> *… if the installer doesn't see a significant profit, they won't bother to do it. So, the lower income households and smaller households get pushed aside if there is a choice between ten small properties and three larger properties, the private installer will go for the three* (FG8:3).

In other focus groups (FG9, FG10), respondents also stressed the importance of cost factors in relation to distributional justice and geographical exclusion:

> *It's very interesting to hear that there are different kinds of hydrogen production. What's disappointing is that in my part of the country it doesn't look like it is going to happen in the foreseeable future* (FG7:3).

This observation underlines the importance of unpacking how the spatial dynamics of the hydrogen switchover and geographical exclusivity may impact social acceptance [63].

Energy cultures and rejection of domestic hydrogen

Although an isolated case in this study, one participant perceived hydrogen as opposing their preferred energy culture [255,256] due to potential risks of being an early adopter or 'guinea pig': "*I don't want to pay for someone else's experiment that may or may not work. I am trying to be energy independent*" (FG8:2). Research on community energy projects [257] and emerging energy cultures in the UK [256,258] remains nascent, therefore, it is challenging to predict what proportion of the population may share similar desires for energy independence, and whether this broadly correlates to residents living in remote locations or hard-to-treat properties [259,260]. An important aspect of supporting a socially acceptable transition [63] lies with better understanding the energy needs of communities located off-grid (~15% of the UK housing stock) [261].

Perceptions of domestic hydrogen futures across focus groups

Based on the poll results, consumers proved highly receptive to the idea of hydrogen homes forming part of the UK's energy future (see Fig. 5 and Appendix G), with around 40% ($N = 23$) and 53% ($N = 31$) answering *somewhat* and *very supportive*, respectively. This finding suggests the proposition of low-carbon hydrogen heating and cooking appliances may be viewed favourably across different segments of the UK population, especially when information provision helps enable a more educated perspective.

The highest level of support for domestic hydrogen was observed among respondents with strong interest in RE and in joining a RE community, and citizens facing fuel poverty ($M = 4.80$), which equated to near unequivocal support. Participants engaged with renewable energy and smart home technologies looked favourably towards the vision of hydrogen in a net-zero future ($M = 4.50$) (see Appendix G). Overall, hydrogen was well received by most respondents in these groups owing to shared perceptions of environmental benefits and positive framings around intergenerational climate justice [262,263] (see Fig. 5).

By comparison, respondents actively engaged in environmental issues recorded the lowest response ($M = 3.90$), seemingly due to underlying reservations concerning the suitability of blue hydrogen, and likely owing to associated factors, such as lack of trust in the government and energy

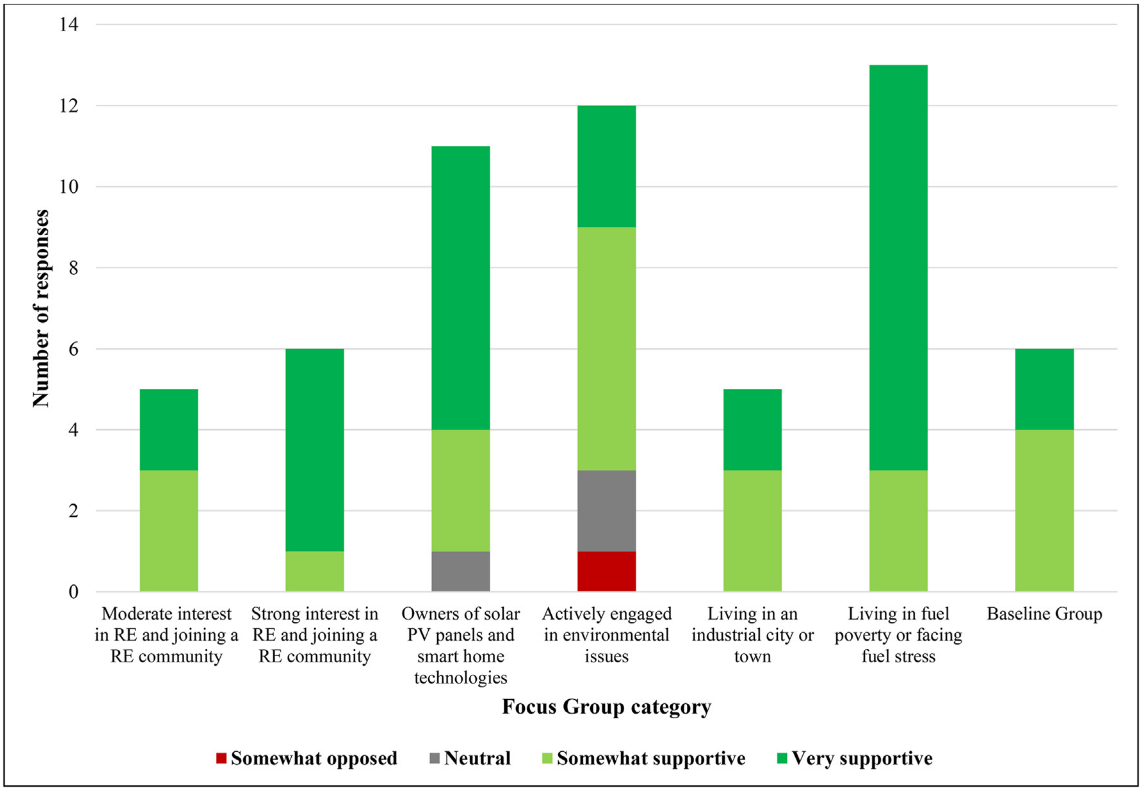

Fig. 5 – Consumer perceptions of hydrogen homes as part of the UK's energy future.

companies for meeting net-zero ambitions (see Fig. 5). Similarly, the baseline group recorded a comparatively lower score ($M = 4.30$) than the remaining focus groups, which suggests that hydrogen acceptance is lower when controlling for factors related to group membership. Overall, the results suggest that engagement in renewable energy, or experiencing fuel poverty may act as critical drivers of domestic hydrogen acceptance.

Consumer messages to stakeholders shaping the hydrogen transition

To conclude the focus group sessions, participants were asked to relay *one key message* to the actors and stakeholders of the hydrogen transition, and relatedly, asked the following: *Imagining a future where you have to choose about using hydrogen, what would you like to know most of all before making a final decision?*

This question triggered a range of responses from around one-third of the sample. The need for increased education and information was cited a total of 9 times, with specific requests for more information from the government and at the grassroots level (see Fig. 6). The other most frequent cited factors included financial implications to households, and impacts related to the environment and sustainability, which included the safeguarding of future generations. The following factors were also singled out by different respondents: appliance performance, energy security, the logistics of boiler replacement, and the quality of hydrogen gas compared to natural gas (see Table 9). Notably, one respondent from the industrial towns group called for "*easy information for people to access which shows a comparison between natural gas and hydrogen*" (FG5:1). This was envisioned as follows:

> *Here is your boiler: here is the initial cost, how much could save, and the carbon footprint reduction. So, a very easy way to compare the shift, something more visual for people so they can see the impact it would have* (FG5:1).

Overall, responses underlined the extent to which the importance of adequate information provision and educational campaigns cannot be overlooked if social acceptance is to transpire (see Appendix H).

Meta-inferences and statistical tests

Previously, we examined hydrogen knowledge and awareness levels across the sample and between genders, also reported consumer preferences for accessing sources of reliable information on hydrogen. This aspect of the study was further emphasised by realying consumer messages to stakeholders shaping the hydrogen transition. As a way of further exploring the relationship between knowledge and awareness and hydrogen perceptions, statistical analysis is performed to see if significant associations exist between variables examined in this study.

Kendall's tau-b (τ_b) correlation test was conducted to explore relationships between variables. Kendall's tau provides an alternative non-parametric test to the Pearson's

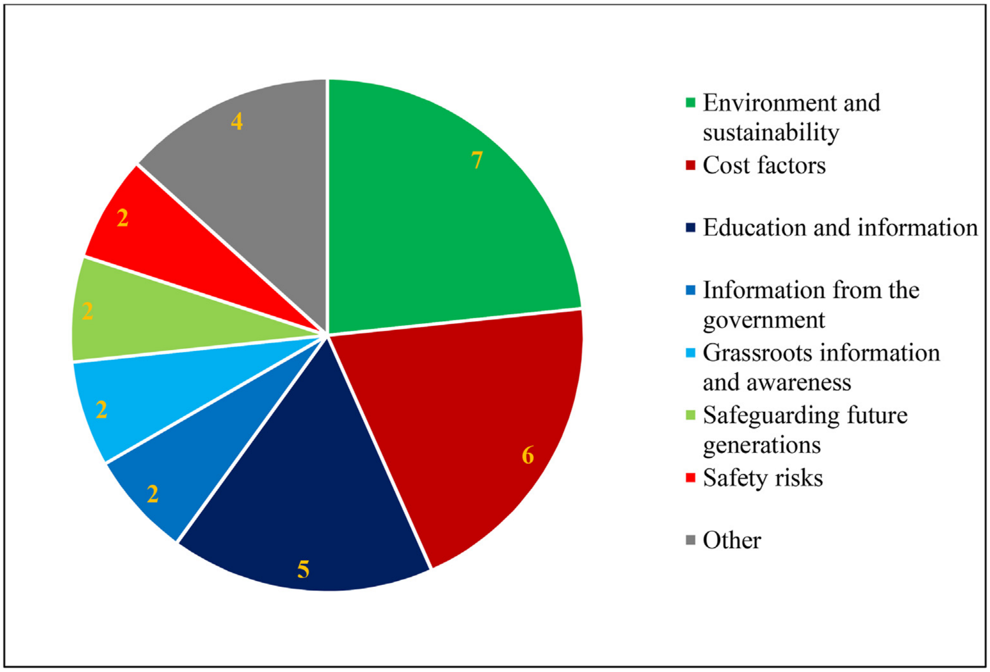

Fig. 6 – Consumer perspectives on informational aspects of the domestic hydrogen transition.

Table 9 – Consumer perspectives regarding the need for specific information on domestic hydrogen.

Participant	Illustrative quotations
FG1:5	• *It needs to be objective, the information – that would be a better approach than greenwashing.*
FG2:1	• *I would want to know that it's sustainable and long-term … and I would want to know about the energy savings … how long is your plan for this? Is it going to be funded and properly moved forward?*
FG2:3	• *I would want to know that it's fully backed and full-proof. Companies are private and can do whatever they want, but if it's backed by the government, I'd be on board or more willing. If I'm going in, I want to know that they're all-in and I'm not the one taking all the risk and funding their venture … does it really live up to the hype or it is going to be another fad? Does it really do what it promised to?*
FG2:6	• *I think it's important to know how hydrogen would affect the UK and whether it would make us more self-sufficient, as opposed to having to import foreign gas. Because look at the price hikes in gas at the moment and everything that's going on with Ukraine.*
FG4:2	• *Would there actually be places where you can go and see it in demo homes? Would the general public have access to see first-hand, to see it and feel it, and use it for yourself?*
FG6:3	• *I didn't know it was possible to have hydrogen in your home. It's been interesting and eye-opening, and I think this is where the future is heading. We need more information like this where we can make up our minds and decide if it's suitable for us, as a family and in our community.*
FG7:3	• *It also depends on the quality of gas that's put out. I remember when we changed from town gas … the natural gas delivered a lot less heat and energy … so that would be something that we'd definitely need to know.*
FG7:5	• *Do you have to put a new one [boiler] in when they say, or do you wait for your existing one to be worn out?*

product-moment correlation coefficient, which is recommended over the Spearman rank-order correlation coefficient (another non-parametric option) for measuring the strength and direction of association between two variables of interest [264,265]. Kendall's tau should be applied when the sample size is small, has many tied ranks, and there is an expected monotonic relationship between variables [264,266,267], which is the case in this study. Statistical tests were carried out for most of the sample, following a high response rate to poll questions (N = 54).

Contrary to evidence in the literature which suggests scepticism towards HETs may be associated with an underlying knowledge or experience gap [82,143], this study observes no significant association between knowledge and awareness and support for domestic hydrogen futures ($\tau_b = .095$, $\rho = 0.445$) or broader hydrogen acceptance ($\tau_b = -0.182$, $\rho = 0.117$). However, knowledge and awareness appear to shape perceptions of the twin-track production approach to a degree. The knowledge and awareness variable[14] showed the following descriptive patterns (see Appendix I), which informed the statistical results: Low knowledge awareness (N = 29, M = 4.31); Limited knowledge and awareness (N = 29, M = 4.10); Some knowledge and awareness (N = 10, M = 3.80); and Moderate to high knowledge and awareness (N = 5, M = 3.00). A weak to moderate, negative correlation was observed between hydrogen knowledge and awareness and perceptions of the twin-track approach, which was statistically significant: $\tau_b = -0.344$,

[14] Converted from the original Scale of 1–4 to Scale of 1–5 by multiplying by a factor of 1.25.

$\rho = 0.004$ (Bootstrap 95% confidence intervals: −0.117 to −0.531). It can be inferred that scepticism regarding the twin-track approach may prove more likely when consumers are older, highly educated males who are environmentally engaged, and not experiencing fuel poverty.

Next, Kendall's tau was performed to test the relationship between the following variables: consumer attitudes towards the twin track approach, (2) consumer perceptions of domestic hydrogen futures, and (3) hydrogen acceptance (the mean score of the former two variables). All three relationships proved significant at the 0.01 level (2-tailed), with the strongest relationship observed between the twin-track approach and hydrogen acceptance, followed by domestic hydrogen futures and hydrogen acceptance (see Table 10). By contrast, the positive association between attitudes towards the twin-track approach and perceptions of domestic hydrogen futures was more moderate. This finding adds weight to the qualitative evidence by suggesting mostly marginal support for the twin-track approach among respondents, which may partially negate support for domestic hydrogen. Fig. 7 visualises these findings based on the aggregate data of the study (see Appendix I), while Table 11 concludes this section by deriving meta-inferences from the mixed methods results.

Table 10 – Kendall's tau results for measures of hydrogen perceptions.

	Twin-track approach	Domestic hydrogen futures	Hydrogen acceptance
Twin-track approach	1		
Domestic hydrogen futures	.496[a,b]	1	
Hydrogen acceptance	.868[a,c]	.749[a,d]	1

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Bootstrap 95% confidence intervals: 0.280–0.676.
[c] Bootstrap 95% confidence intervals: 0.808–0.921.
[d] Bootstrap 95% confidence intervals: 0.635–0.845.

Discussion

This paper presents mixed methods insights on consumer perceptions of domestic hydrogen futures in the UK context, with a focus on public knowledge and awareness of hydrogen, and the government's Hydrogen Strategy, specifically, the twin-track production approach. Analysis and comparison of focus group transcripts, alongside statistical analysis of poll data, provide integrated findings on hydrogen perceptions. The findings speak to the importance of raising public awareness and consumer engagement to help alleviate scepticism, concerns, and preconceived notions about hydrogen which could otherwise stifle a potential transition to hydrogen homes. The results also caution that much of the public is yet to engage with hydrogen beyond a surface level, if at all, which should put the government and industry on red alert about diffusing hydrogen into the public consciousness, in alignment to the energy security, fuel poverty, and net-zero agendas.

To alleviate scepticism and concerns, information campaigns should ensure greater transparency regarding the benefits, costs, and risks of the transition, with clearer communication on the timeline of the potential roll-out and

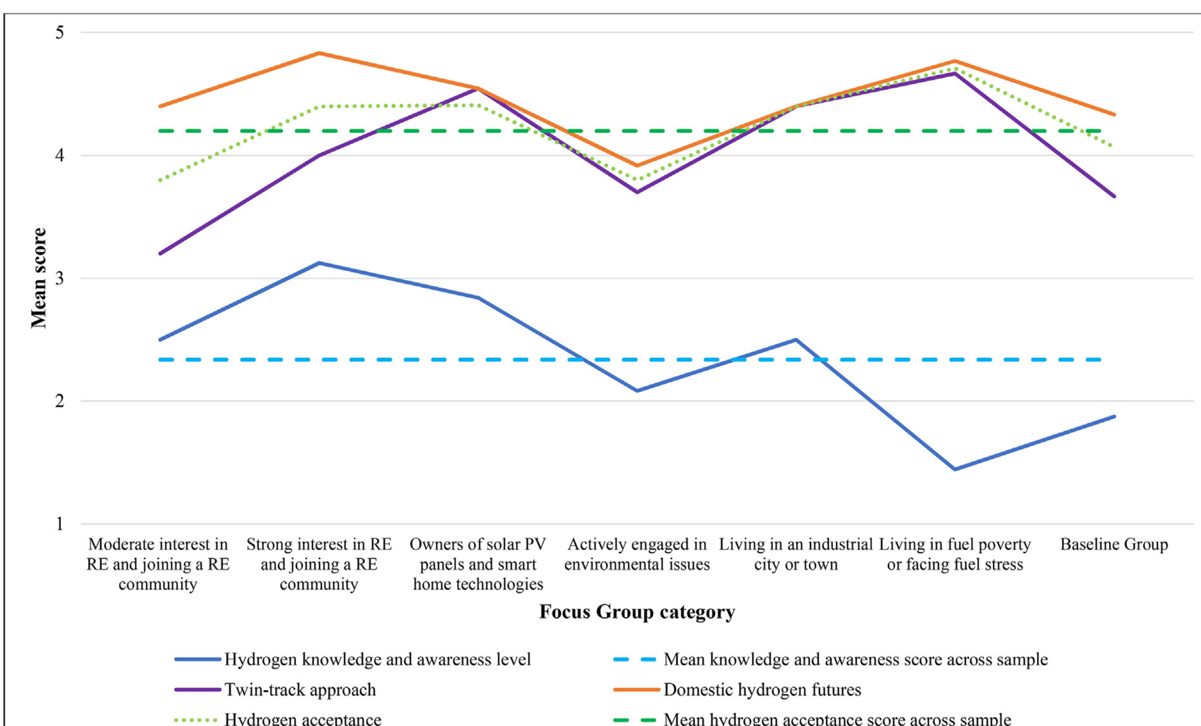

Fig. 7 – Measure and comparative assessment of domestic hydrogen acceptance across focus groups and sample.

Table 11 – Meta-inferences on hydrogen perceptions from mixed methods, multigroup analysis.

Research question	Quantitative inferences	Qualitative inferences	Meta-inferences
RQ1 What is the existing level of hydrogen knowledge and awareness among UK consumers? (RQ1a); and what preferences do UK consumers have for information dissemination on hydrogen? (RQ1b)	• Limited or low levels of knowledge and awareness across most of the sample, with younger respondents appearing less informed • Hydrogen knowledge and awareness is positively associated with ownership of solar PV panels and smart home technologies, and broader engagement in renewable energy • Younger citizens facing fuel poverty are mostly unfamiliar with hydrogen	• Existing hydrogen knowledge and awareness typically stems from high school science education (especially for older respondents) and media coverage (television and internet) • Hydrogen for transport applications is more familiar than use for domestic heating and cooking purposes	• Hydrogen, particularly for domestic applications, is yet to enter the public consciousness • Social representations of hydrogen remain relatively malleable for most consumer segments • UK citizens appear largely receptive to learning more about hydrogen and express a proactive attitude towards information dissemination • Hydrogen perceptions may be shaped positively by targeted education campaigns led by the government, business, and industry • Parallel information dissemination and consumer engagement is required through grassroots channels to build market confidence and trust • Consumers request further information on environmental and sustainability aspects, cost factors, and safety
RQ2 What perceptions do consumers hold towards the UK government's twin-track approach entailing blue and green hydrogen production pathways?	• Close to half of the sample express a *somewhat supportive* position for the twin-track approach, while one-third appear *very supportive* • Support levels are highest for respondents facing fuel poverty, living in industrial towns, and owning solar PV panels and smart home technologies, whereas participants actively engaged in environmental issues expressed comparatively lower levels of support	• Support stems from seeing the UK Hydrogen Strategy and the twin-track approach as a positive milestone and step towards delivering net zero • Concerns and scepticism are attributed to perceptions that the twin-track approach is non-committal to a renewable future and may lock in reliance on natural gas	• Support for the twin-track approach has a moderate positive effect on consumer perceptions of domestic hydrogen futures, and a strong, positive effect on underlying hydrogen acceptance • Location and income may shape approval rates for the twin-track approach, with industrial areas and households experiencing fuel poverty appearing more inclined to support the government's vision • Engagement in environmental issues may provoke concerns over the legitimacy of blue hydrogen and thereby diminish hydrogen acceptance • The government should take steps to justify the environmental grounds for the twin-track approach and publicise the rationale to the wider public, through national media coverage and other outlets such as non-governmental organisations

Table 11 – (*continued*)

Research question	Quantitative inferences	Qualitative inferences	Meta-inferences
RQ3 How do consumers perceive the prospect of domestic hydrogen as part of the country's low-carbon energy future?	• Respondents express overwhelming support for hydrogen in the UK's energy future, with 31% answering *very supportive* and 62% *somewhat supportive* • Support levels increase with interest in renewable energy, and conditions of fuel poverty	• A lack of education and information is cited as the main barrier to social acceptance, with respondents stressing the need to increase clear and transparent information on domestic hydrogen • Hedonic and egoistic values related to financial factors and material needs typically outweigh environmental concerns when considering the adoption of hydrogen appliances and support for the transition	• Support for domestic hydrogen is higher than for the twin-track approach across the sample and for most focus group categories, and thereby has a stronger positive association with hydrogen acceptance • The prospect of converting parts of the UK housing stock to hydrogen homes should be coupled more strongly to the potential socio-economic benefits of the transition • Key actors and stakeholders should advance a strategic communication campaign which better situates the environmental benefits of hydrogen and the importance of net zero within the broader discussion of energy security and fuel poverty • Alternative options for decarbonising homes such as heat pumps and district heat networks should be advocated for, in parallel, when promoting the prospect of hydrogen homes • Special attention should be paid to households located in rural areas, especially off-grid, as well as fuel poor and vulnerable parts of society, as a means for enacting a fair and socially acceptable pathway for residential decarbonisation

emissions reduction. In response, social marketing and education campaigns should communicate the positive socio-economic aspects of hydrogen [60], while informing consumers about core safety and environmental credentials [19,66]. Optimally, such campaigns should account for specific challenges and opportunities associated with different geographical areas [19,160,190], socio-demographic groups [64,178,268], energy cultures and attitudes [66,255,269].

It follows that domestic hydrogen acceptance will rest on how public knowledge and awareness shape consumer perceptions of hydrogen's environmental credentials in relation to respective production pathways, among a myriad of other key factors. Underlining this critical point, one respondent expressed a position which may reflect certain segments of UK society, and will need to be internalised by the government when delivering their long-term hydrogen strategy:

> *For me, it was hearing about blue hydrogen and the reliance on fossil fuels, which I wasn't aware of. For me, we need to be moving to constant renewable or green energy to give us that hydrogen. So, that surprised me from all the information from tonight* (FG5:1).

While there is some encouragement for and wider openness to pursuing the twin-track strategy, parts of society are likely to call for stronger commitment towards a greener pathway. Scepticism over blue hydrogen appears more probable when consumers are actively engaged in environmental issues. Similarly, respondents with awareness of UK energy and environmental policy may question the merits of the twin-track approach, potentially viewing it as non-committal to decarbonisation efforts. Negative perceptions of the twin-track strategy also tie into an emerging awareness of intergenerational climate justice, which may prove more prevalent among families with grandchildren. Nonetheless, personal considerations around cost factors typically supersede concerns around climate change and the environment. Consequently, when requesting critical information on domestic hydrogen, consumers principally cite cost factors and safety implications, and in some cases, environmental impacts.

At a general level, the public is encouraged by the launch of a national hydrogen strategy, perceiving it as a positive measure for climate change mitigation and energy security. However, public support for hydrogen homes is largely contingent on cost savings for consumers, and to a lesser degree, rests on the contribution of hydrogen to net zero. The potential relevance of this finding is especially noteworthy, given that environmental issues appeared to resonate strongly with participants across all focus groups [270]. Finally, evidence also suggests that respondents recognise the importance of a fair hydrogen transition. Most notably, citizens value safeguarding the needs of vulnerable members of society throughout all stages of the switchover. At the same time, there is growing awareness that "*a more holistic approach*" is needed to offset the pitfalls of "*a one-size-fits-all approach*" (FG1:5).

This research supports active engagement with different segments of the population, as a mechanism for facilitating a more inclusive and insightful debate on the implications of hydrogen production pathways and the deployment of hydrogen homes [178]. Critically, the notion of competing or complementary hydrogen production pathways must shift beyond academic and policy debates [107,112,271,272] by entering the public discourse in a meaningful way, so that propositions such as the twin-track approach can be understood and responded to. For this to transpire fully, policymakers, industry actors, and other key stakeholders must first dedicate sufficient resources to moving the dial on hydrogen knowledge and awareness. Until this happens, there is a risk that the twin-track approach may be viewed as somewhat incompatible with supporting a net-zero society, thereby undermining conditions for domestic hydrogen acceptance.

As a starting point, information campaigns should communicate the potential merits of combining two or more hydrogen production pathways, thereby dispelling misconceptions among parts of the public that a multi-pronged production approach is non-committal. Should a negative social representation of the twin-track approach manifest within the public consciousness, there is palpable risk of consumer resistance towards the domestic hydrogen switchover, which may undermine the broader transition to a national hydrogen economy. As Betsen et al. [31:10] argue in the Norwegian context:

> Lacking or ambiguous communication concerning projects using grey, and to a certain degree blue hydrogen, could lead to an opinion backlash regarding new hydrogen technologies, as well as reduced trust in politicians and companies if the proposed projects do not align with the public's expectations of emission reductions.

In parallel, policymakers and GDNOs must achieve their intended goals of demonstrating the viability of hydrogen home appliances across parts of the housing stock, while engaging local communities in the transition process and, as underscored within this study, factoring consumer heterogeneity into the development of hydrogen village trials.

Conclusions

This study focused on several key aspects of domestic hydrogen acceptance, including consumer preferences regarding hydrogen production pathways, the logistics of the switchover, and informational processes. The results align with the wider literature in several ways: (1) relatively low levels of hydrogen knowledge and awareness were reported among the sample; (2) the main source of hydrogen knowledge is media coverage, particularly news reports; (3) hydrogen transport applications, especially HFCVs, were more familiar among the public than other use cases; and (4) males above 30 years old appeared the most knowledgeable demographic group.

Additionally, this study reveals more nuanced findings which link hydrogen engagement levels to observed generational gaps. In some situations, hydrogen knowledge is being partially disseminated by the younger generation in active education, whereas for some older members of society, hydrogen awareness may be restricted to vague associations from high school chemistry. When this is the case, there may also be more grounds for scepticism due to historical associations with explosive incidents and subsequent fear of hydrogen [172,175]. Qualitative insights also suggest that households may perceive hydrogen as a less disruptive decarbonisation pathway than heat pumps, nevertheless, consumers are interested to understand more about disruptive impacts. Furthermore, location appears to influence consumer perspectives, with respondents from industrial areas within the vicinity of hydrogen clusters expressing high levels of support for both the twin-track approach and domestic hydrogen futures. By contrast, as proximity from hydrogen hubs decreases, consumers are more conflicted about the transition, especially when living in rural locations, south of London or in South Wales.

The findings of this research can be transferred to other countries considering a similar hydrogen transition pathway to the UK, and frontrunner nations exploring the merits of different hydrogen production pathways (see Section Introduction). Nevertheless, as an explorative qualitative study, this paper is not without limitations and the generalisability of results should be attested to by undertaking national survey studies and cross-country comparative research. Firstly, alternative target groups can be engaged with, such as consumers in more rural parts of the country or with different housing characteristics, thereby helping to inform different aspects of policymaking. Similarly, different approaches could be taken to access richer insights into consumer perspectives of one specific aspect of the hydrogen transition, such as the environmental implications of distinct production pathways. Framings should also extend beyond the parameters of the twin-track approach by including alternative pathways such as nuclear-based hydrogen production where relevant [187].

Such a reframing would call for different information provision materials and may benefit from a more interactive focus group or workshop format, wherein consumer perspectives are gauged in a more longitudinal sense, before and after information exposure. At the same time, a follow-up study in the UK context should verify whether the updated British Energy Security Strategy, specifying at least 50% green hydrogen production for the 2030 target, has influenced consumer attitudes towards the twin-track approach. Moreover, future research should integrate quantitative data collection procedures through large sample surveys to help substantiate the robustness of qualitative insights from this study. Specifically, we advocate for employing partial least squares structural equation modelling (PLS-SEM) [273,274] to explore and validate the antecedents of hydrogen acceptance

[275,276]. Such contributions would enhance meta-inferences derived from qualitative findings and compensate for the limitation of a small-sample study, which is otherwise constrained to the boundaries of the recruitment process and research design [277].

Moving forward, social scientists should call upon the full repertoire of available research methods, and innovate new research procedures, to better gauge how the difficult choices facing the hydrogen transition may be perceived and received by different consumer segments and the public at large. Additional MMR, employing a multigroup analysis approach, can help ascertain the extent to which specific hydrogen production pathways may garner social acceptance across different consumer segments. Future studies should further investigate whether this support translates into broader approval for the domestic hydrogen transition and willingness to adopt hydrogen homes appliances. For the time being, there remain serious question marks over whether the twin-track approach, as currently understood by the public, will prove compatible with hydrogen acceptance, both at the socio-political and individual level.

Data availability statement

Data underlying this study can be accessed through the Cranfield University Online Research Data (CORD) Repository at:

https://doi.org/10.17862/cranfield.rd.20727982.v1
https://doi.org/10.17862/cranfield.rd.21081670.v1
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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.06.297.

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