Renewable and Sustainable Energy Reviews 188 (2023) 113810

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Price promises, trust deficits and energy justice: Public perceptions of hydrogen homes

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ARTICLE INFO

Keywords:
Decarbonisation
Energy justice
Energy transitions
Hydrogen economy
Public trust
Social acceptance

ABSTRACT

In an era characterised by political instability, economic uncertainty and mounting environmental pressures, hydrogen fuel is being positioned as a critical piece of the global energy security and clean energy agenda. The policy push is noteworthy in the United Kingdom, where the government is targeting industrial decarbonisation via hydrogen, while exploring a potential role for hydrogen-fuelled home appliances. Despite the imperative to secure social acceptance for accelerating the diffusion of low-carbon energy technologies, public perceptions of hydrogen homes remain largely underexplored by the researcher community. In response, this analysis draws on extensive focus group data to understand the multi-dimensional nature of social acceptance in the context of the domestic hydrogen transition. Through an integrated, mixed-methods multigroup analysis, the study demonstrates that socio-political and market acceptance are strongly interlinked, owing to a trust deficit in the government and energy industry, coupled to underlying dissatisfaction with energy markets. At the community level, hydrogen homes are perceived as a potentially positive mechanism for industrial regeneration and local economic development. Households consider short-term disruptive impacts to be tolerable, provided temporary disconnection from the gas grid does not exceed three days. However, to strengthen social acceptance, clearer communication is needed regarding the spatial dynamics and equity implications of the transition. The analysis concludes that existing trust deficits will need to be overcome, which entails fulfilling not only a 'price promise' on the cost of hydrogen appliances, but also enacting a 'price pledge' on energy bills. These deliverables are fundamental to securing social acceptance for hydrogen homes.

1. Introduction

Hydrogen is increasingly considered as a potentially critical industrial feedstock and energy vector [1] for securing a decarbonised global energy future [2,3]. Within recent years, this growing recognition has translated into the launch of national hydrogen strategies [4,5] in over 30 countries [6] spanning much of the globe [7].[1] Additionally, regional hydrogen strategies and action plans have been formulated in countries such as Canada [8,9], Australia [10–12], and the UK [13–15], while roadmaps are also emerging across parts of Africa [16–18]. Considering that Japan was the first country to launch a national hydrogen strategy in December 2017 [19] while the United States formalised its strategy and roadmap in June 2023 [20], it is apparent that the long-held notion of a global 'hydrogen economy' [21–23] is gaining international traction.

The advent of hydrogen economies could prove especially crucial to European countries with large-scale natural gas infrastructure [24], including Germany [25,26], the Netherlands [27,28], and UK [29,30]. Critically, such countries face the dual challenge of mitigating energy security pressures [31–33], while fulfilling climate change commitments [34,35]. The emerging policy push for a low-carbon hydrogen economy is noteworthy in the UK context [36] where the government is supporting a cross-cutting strategy through its 'twin-track' approach, envisioning pathways for both 'blue' and 'green' hydrogen production [29].[2] Despite uncertainties over the feasibility of hydrogen production pathways [37,38], end-use applications [39], and climate change-related impacts [1,40,41], there is a consensus that clean

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[1] Including North America [20,366], Oceania [367,368], much of Europe [25,27,29,369–371], and parts of the Middle East [372,373], Asia [19,374,375] and South America [376,377].

[2] Blue hydrogen relies on steam methane reformation (SMR) with carbon capture and storage (CCS) [378–380], while green hydrogen is produced using water electrolysis sourced from renewable energy sources [381–383].

https://doi.org/10.1016/j.rser.2023.113810
Received 4 October 2022; Received in revised form 31 August 2023; Accepted 1 October 2023
Available online 12 October 2023
1364-0321/

Nomenclature

CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
GDNOs	Gas Distribution Network Operators
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air-conditioning
$MtCO_2$	Million tonnes of carbon dioxide
Ofgem	Office of Gas and Electricity Markets
RE	Renewable energy
REMA	Review of Electricity Market Arrangements
SMR	Steam methane reformation
TUC	Trade Union Congress
WTP	Willingness-to-pay

hydrogen technologies can accelerate decarbonisation across 'hard-to-abate' sectors, such as heavy industry [42,43] and heavy-duty transport [44,45].

At present, UK policy makers envision a national hydrogen economy established through synergies between industrial, power, transport, and residential applications [29,39]. This vision [14,29] rests on leveraging the country's natural gas reserves [46,47] and related infrastructure [30,48,49], industrial base [50,51], technological innovation capabilities [52,53], and offshore wind potential [36,53,54] to enable a rapid scaling up of hydrogen energy systems. Although industrial decarbonisation remains the immediate priority [29,39], the UK government is also deliberating the potential role of hydrogen-fuelled appliances for domestic space heating, hot water, and cooking [55], as part of a hybrid decarbonisation strategy [56,57].

While the government is set to take a strategic decision on the role of domestic hydrogen in 2026 [29], the current outlook is somewhat pessimistic following recent local opposition to hydrogen village trials in the North of England [58–61]. In July 2023, consumer resistance culminated in the cancellation of a planned hydrogen trial for Whitby village in Ellesmere Port (Cheshire) [62],[3] which may have been pre-empted by a more comprehensive understanding of social acceptance dynamics. However, due to the nascency of hydrogen home appliances [63,64], the social science research agenda on domestic hydrogen acceptance [65] remains embryonic [66]. Emphatically, Palomo-Vélez et al. [67] underline how a deficit in "public support can grind energy projects to a halt," while impeding the implementation of associated energy policies [67]. Foremost, events in Whitby provide a cautionary tale of what may unfold when social acceptance is insufficiently understood and accounted for. Foreseeably, the cancellation of the Whitby trial has hindered prospects to deploy hydrogen homes, which may impact the wider trajectory of the national hydrogen economy.

Against a volatile socio-political landscape and socio-economic environment [68] in which energy security is a focal point [69–71], this research examines public perceptions of domestic hydrogen [72,73] across dimensions of socio-political, market, community, and household acceptance [74–77]. The underlying objective is to evaluate consumer attitudes towards hydrogen homes by examining acceptance dynamics in relation to critical factors such as public trust, financial perceptions, community benefits, disruptive impacts, and equity implications [73, 75]. The study evaluates respective acceptance dimensions to assess which areas may be most at-risk and for which parts of society.

Recognising that the 'human dimension' of technology acceptance [78–80] will shape energy transition pathways [81–84], this study is motivated by the need to bridge a critical knowledge gap on public perceptions of hydrogen homes [73]. Deeper comprehension of this topic may entail important implications for 'hydrogen futures' [85,86] and global decarbonisation pathways [87–90]. The study draws on qualitative data from a series of online focus groups conducted between February and April 2022 to engage with hydrogen perceptions in the UK context. In doing so, this contribution supports the call for empirical analysis on hydrogen acceptance [77,91,92], while engaging with the contested discourse around residential decarbonisation pathways [93, 94]. The research design facilitates an integrated, mixed-methods multigroup analysis, whereby several consumer segments compose the sample ($N = 58$), enabling opportunities for comparative assessment across a range of social acceptance metrics.

The rest of the study is structured as follows to fulfil its aim and objectives. Section 2 outlines the macro- and micro-level implications of transitioning to hydrogen homes. Section 3 reviews the literature on socio-political, market, community, and household acceptance of low-carbon energy technologies [74] and hydrogen energy technologies [73,75]. Section 4 describes the methodology, while Section 5 reports key findings on domestic hydrogen acceptance based on the statements of focus groups participants. Section 6 discusses critical insights on different dimensions of domestic hydrogen acceptance. Section 7 concludes the study by highlighting implications for stakeholders and opportunities for future research.

2. Macro- and micro-level implications of hydrogen homes

2.1. Trends in UK carbon emissions and decarbonisation policy

Currently, domestic heating is responsible for approximately 14 % of total UK carbon emissions, whereas cooking contributes to around 2 % [95].[4] Addressing the carbon footprint of the residential sector entails rapidly phasing out 21.2 million gas boilers and 12.7 million gas cookers (hobs and ovens) [96,97] currently installed across 84 % of the housing stock (~23 million properties) [96,98],[5] in addition to decarbonising off-grid properties [72,99]. Countering this imperative, around 1.67 million gas boilers were purchased by UK consumers in 2019 [100].[6] In view of these trends, it is evident that a portfolio of low-carbon energy technologies such as heat pumps, district heating, and possibly hydrogen will be needed to decarbonise the UK housing stock [99,101] in support of net-zero ambitions [102,103].

Supporting the vision for low-carbon heating, a policy ban on gas and oil boilers in newbuild homes is expected to be imposed by 2025 [104]. In parallel, the UK's leading boiler manufacturers are currently developing 'hydrogen-ready' boilers, which are expected to be price competitive with existing gas boilers [105,106]. Specifically, the market price of hydrogen boilers could reach parity with gas boilers before 2030 [107], as supported by a recent 'price promise' made by the boiler industry's 'Big Four' (Worcester Bosch, Vaillant, Baxi, and Ideal) [108].

At the macro-level, the domestic hydrogen transition would involve repurposing the UK's national gas grid to support the transmission and distribution of hydrogen [109–111], as reflected by growing ambitions for developing 'hydrogen backbones' (i.e. large-scale, interconnected pipeline systems) [112,113] and regional hubs around major industrial clusters [114–116]. At the micro-level, transitioning to 'hydrogen homes' [117,118] entails deploying low-carbon boilers and cooking

[3] The cancellation was made effective by Energy Minister, Lord Callanan [59].

[4] Between 2014 and 2018 energy consumption and emissions from domestic space heating increased by 9 % and 8 % Geels [327], followed by a 2 % increase in domestic energy use during the COVID-19 pandemic in 2020 [384].

[5] Around 30 % of the country's housing stock (~8.5 million properties) is classified as 'hard-to-treat' [385], contributing towards around 50 % of household emissions [386].

[6] Representing an estimated 7 % of grid-connected properties [56].

appliances [55] to support the 'deep' decarbonisation of the residential sector [75,119,120].

Although proponents of hydrogen argue that it could provide a relatively non-disruptive and cost-effective pathway for decarbonising homes [121], the techno-economic feasibility of domestic hydrogen is yet to be established [24,122]. Barriers to hydrogen technology deployment such as safety and cost will need to be overcome to support a socially acceptable transition [24]. As articulated by Jones et al. [123], addressing constraints and bottlenecks to technology diffusion calls for "increased collaborative research between social scientists, pure scientists and engineers" [123]. As a social science contribution, this study aligns to the call for integrating consumer acceptance into assessments of technology adoption [77,124], but makes no assumptions about the techno-economic feasibility of deploying hydrogen homes at scale.

2.2. Trends in the energy price cap

Establishing techno-economic feasibility and social acceptability are less probable during times of political and economic instability [125], adding to the challenge of enacting a clean hydrogen economy within a net-zero timeframe [126]. This study coincides with a time of extreme political and economic instability, compounded by the COVID-19 pandemic [71,127],[7] Russia-Ukraine conflict [31,32,128], and a host of 'threat multipliers' [70,129], which have culminated in an unprecedented energy crisis [130], as demonstrated in Fig. 1. During 2021 nearly 30 energy companies went bankrupt in the UK, affecting over four million customers [131,132]. Continuing the previous year's trend, Bristol Energy collapsed at the start of 2022, displacing an additional 176,000 customers [131,132]. Following these developments, the energy price cap (EPC)[8] increased by £139 (~12.2 %) in October 2021, before reaching £1971 in April 2022 [69]. Shortly after, forecasts suggested the next EPC would exceed £3000 [69,130,133], giving rise to concerns that the number of households facing fuel poverty could double from 6.5 to 12 million [69].

In October 2022, the EPC reached £3549; coinciding with the introduction of an energy price guarantee (EPG)[9] of £2500 to help alleviate economic pressures. Thereafter, the EPC peaked at £4279 in January 2023 before falling to £3280 in April 2023, while the EPG remained in place. Reflecting seasonal demand for heating, the latest EPC for July to October 2023 is set at £2,074, while the EPG has been increased to £3000 and will remain in place as a safety net until the end of March 2024. Given recent trends, there are prevailing concerns that previous fuel poverty estimates could further increase by the end of 2023 [134,135].

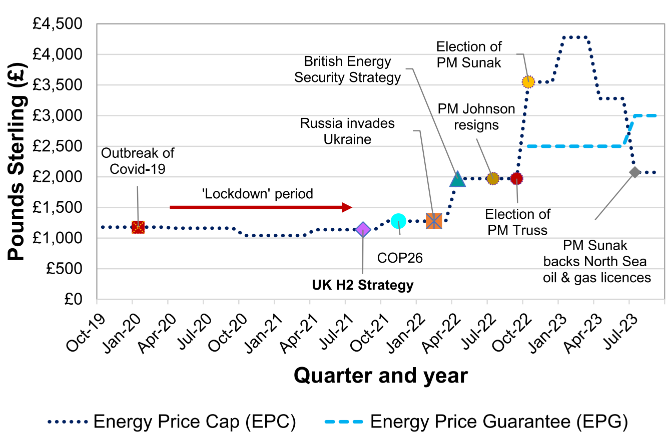

Fig. 1. Overview of political and economic developments affecting UK energy markets.

Unprecedented fluctuations in the EPC over the past 18 months (see Fig. 1) have led to emerging energy security policies, such as ambitions for up to 50 GW of offshore wind capacity by 2030 and 24 GW of new-build civil nuclear generation capacity by 2050 [53], alongside recent plans for hundreds of new North Sea oil and gas licences [136]. Such developments will have notable implications for prospective hydrogen production pathways [29]. Against this background, Section 3 further contextualises the study by reviewing the literature on socio-political, market, community, and household acceptance [73,74,77] for low-carbon and hydrogen energy technologies. As argued throughout the study, the emerging contours of hydrogen acceptance may yield important implications for the trajectory of UK energy policy.

3. Dimensions of social acceptance

Traditionally, international energy studies have engaged with the socio-political, market, and community dimensions of social acceptance [137–139], following "the triangle of social acceptance of renewable energy innovation" proposed by Wüstenhagen et al. [74] in 2007. Notably, the framework was initially developed to better understand community responses to onshore wind projects [74,140], but has since been applied to a wide range of energy technologies [76,123,137] and contexts [141–143].

In a recent contribution, Gordon et al. [75] incorporated additional dimensions of attitudinal and behavioural acceptance when conceptualising a novel multi-dimensional framework for examining domestic hydrogen acceptance. The framework integrates socio-psychological and socio-cultural factors [75], alongside socio-political, economic, and contextual factors embedded within traditional acceptance dimensions [73], thereby elevating the role of consumers in household energy adoption. Following the tenets of the five dimensions framework [75], the next sub-sections engage with social acceptance at the socio-political, market, community, and household level, reflecting the conceptual approach visualised in Fig. 2.

3.1. Socio-political acceptance: public trust in the low-carbon transition

Socio-political acceptance rests on the extent to which consumers view domestic hydrogen appliances as "a legitimate and just technology pathway" for improving society, the economy, and environment [75]. A key component of socio-political acceptance for the low-carbon energy transition is public trust [89,144,145]. While public trust[10] is a nuanced [146] and multi-dimensional concept [147,148], it essentially reflects the degree to which society perceives stakeholders to have public-serving motives [67,149] linked to levels of competence and integrity [145,150,151].

Drawing on recent examples, the government announced a moratorium on fracking in 2019 following local opposition [152], while the nationwide smart meter roll-out continues to face consumer resistance due to public mistrust, which has stifled market uptake [153–155]. Furthermore, it is possible that the cancellation of the Whitby village trail could lead to negative 'spillover' perceptions [156] towards other parts of the hydrogen economy. Reflecting this prognosis, Aditiya and Aziz [157] note the extent to which "low public trust is a potential hindrance" when aiming to introduce sustainable hydrogen

[7] The UK's first two patients tested positive for Coronavirus on January 29th, 2021.

[8] Set twice a year and regulated by the Office for Gas and Electricity Markets (Ofgem) to a limit the unit rate and standing charge that energy suppliers can charge for standard variable tariffs.

[9] A government subsidy introduced to limit the charges per unit of gas or electricity.

[10] We refer exclusively to 'public trust' throughout the study and consider this term to be interchangeable with 'social trust' in the context of this analysis.

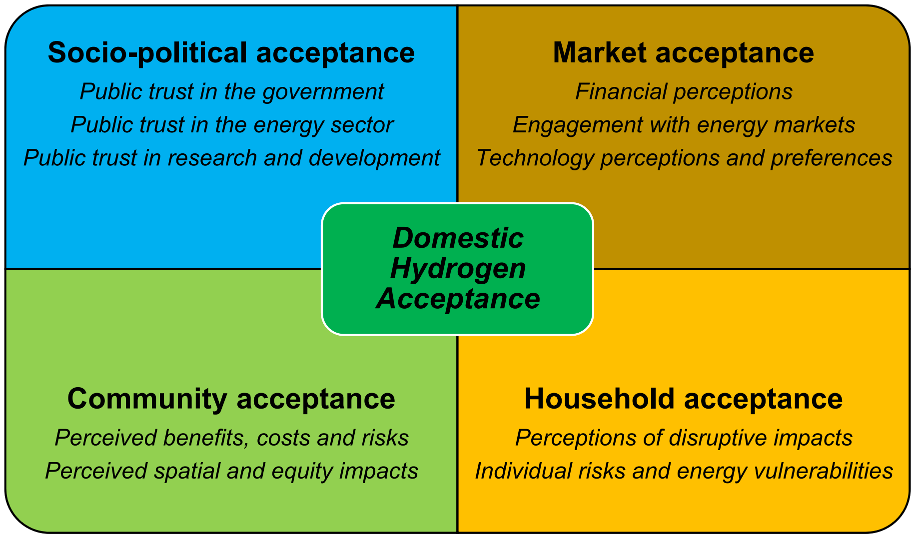

Fig. 2. Conceptual framework for examining domestic hydrogen acceptance.

technologies, while Dwyer and Bidwell [158] emphasise the importance of public trust to scaling up renewable energy (RE) projects. Accordingly, the cancellation of the Whitby village trial may diminish public confidence in hydrogen homes, as well other sectors of the hydrogen economy.

Contrary to renewed policy commitments towards climate change targets [50,102,103], data suggests public trust in net-zero actors including the UK government remains low [159,160]. Public trust in further constrained owing to a lack of confidence in energy suppliers [78,161–163]. In 2020, Ofgem [164] reported that only 35 % of consumers ($N = 4608$) were trusting of energy companies compared to 45 % in 2019, while 28 % expressed distrust.[11] While these trends can be partly attributed to the socio-economic repercussions of COVID-19 [164], mistrust stems primarily from negative public perceptions concerning the profit motives of the energy industry [160,165]. Similarly, in the Dutch context, the intentions of energy suppliers to reduce CO_2 emissions has been met with public scepticism [149]. Moreover, the government is sometimes considered complicit due a lack of regulation and legal enforcement to help curb opaque business practices [166,167].

Recent hydrogen acceptance studies conducted in the UK [163,168] reflect the extant deficit in public trust. Employing a seven-point Likert scale (1 = strongly disagree; 7 = strongly agree) Van Alstine and Bastin [168] found that survey respondents in the North of England ($N = 578$) were doubtful whether the national government ($M = 3.7$), as well as local councils ($M = 4.0$), could be trusted to make competent decisions about hydrogen deployment. Similarly, Sovacool et al. [89] found that only 40.6 % of UK respondents ($N = 2000$) regarded the government as a trustworthy entity, whereas this figure increased to 50.4 % for scientists. Conversely, consumers are typically more trusting of local tradespeople and professionals [89,169,170].

Critically, the public remains sceptical about the commitment of government and industry towards facilitating distributional and procedural justice [73,160] (i.e. a socially just distribution of resources and benefits, and fair and inclusive planning processes). Nevertheless, the public expect these entities to ensure stringent management of health, safety, and environmental issues [163,171]. Supporting this assessment, the study of Van Alstine and Bastin [168] reported stronger levels of public trust in the notion that hydrogen technologies would only be introduced if safe ($M = 5.1$). To derive deeper insights regarding the trust dynamics of the domestic hydrogen transition, Sections 5.1 examines qualitative evidence regarding public trust in the UK government, while Section 5.2 broadens the discussion to perceptions of other key actors and stakeholders, such as energy companies, gas distribution network operators (GDNOs), boiler manufacturers, and research institutes.

3.2. Market acceptance

When purchasing energy-efficient appliances [172], households operate as both investors and consumers [74]. Consequently, market acceptance entails a combination of economic and social factors [75, 137] involving financial perceptions, consumer engagement in energy markets, and technology choice and personal preferences, which are reviewed in the following sub-sections.

3.2.1. Financial perceptions

The broader literature on hydrogen energy acceptance [77,91], including studies on hydrogen fuel cell vehicles [173], highlights the importance of economic factors [174] and associated financial perceptions [77,91]. These observations are also consistent with studies on low-carbon energy technologies, which find financial factors to be the most critical barrier to consumer acceptance [175].

Market development for hydrogen homes is contingent on interactions between several key stakeholders across the supply chain and a range of intermediaries [24]. However, prospects for market uptake may ultimately be determined by two key factors: the ability and willingness of consumers to invest in hydrogen appliances [24,73]; and the extent to which potentially higher taxes and energy bills may potentially offset the ability or willingness-to-pay (WTP) for domestic hydrogen [72,78,176].

Independent sources estimate the total costs of the hydrogen conversion to lie between £3000 to £3300 for the average UK home [177, 178].[12] These figures suggest that hydrogen home appliances would be cheaper than heat pumps in terms of up-front costs [178–180]. Additionally, it is forecasted that the market price of hydrogen boilers should reach parity with gas boilers before 2030 [107], as supported the industry's recent price promise [108].[13] While uncertainties remain

[11] Trust in the energy sector to treat customers fairly and to charge a fair price was also limited to around 40 %, while around one-quarter of respondents expressed distrust [164].

[12] It is expected that hydrogen appliances and labour will account for around half and one-third of total costs, respectively [177].

[13] Similarly, the price of heat pumps is anticipated to decline as the market develops and economies of scale are achieved domestically [387,388].

regarding cost impacts [24,29,181,182], evidence suggests financial perceptions will prove a critical factor of domestic hydrogen acceptance [73,78,183], especially for households facing economic hardship [176,184] and fuel poverty [71].

At present, research evaluating financial perceptions for hydrogen home appliances remains scarce [73], with evidence limited to studies in the UK [163,168,176,185], Australia [186–188], and Europe [89,189]. Surveying consumers in five European countries in 2020 ($N = 10,109$), Sovacool and colleagues [89] reported that 17.6 % of UK respondents ($N = 2000$) would be willing to pay €20/month more (equivalent to about £200/year) on their bills for low-carbon heating, compared to 46.9 % among Swedish respondents,[14] however the study failed to distinguish between technology types (e.g. biomass boiler, heat pump, district heating).[15] By contrast, a hydrogen-specific study conducted in the same year (2020) within the UK ($N = 1027$) reported relatively low levels of concern about the switchover leading to a 7 % increase in gas bills [185]. However, it should be stressed that both studies were conducted prior to the current energy crisis, which infers WTP has likely decreased since 2020.

Despite the imperative to quantify and unpack consumer perceptions of cost factors, there remains a lack of concrete evidence on this aspect of the hydrogen transition; beyond the acknowledgement that government subsidies and financial schemes are imperative to realising a low-carbon domestic energy future [168,185]. Although forecasting future hydrogen production costs is subject to significant uncertainty [190] and further compounded during times of political and economic crises [70,191], efforts must be taken to ensure hydrogen acceptance is examined meaningfully by accounting for WTP.

Context-specific analysis on market acceptance, as presented within Sections 5.3 and 5.4 of this study, can help validate whether UK consumers may have a higher WTP for low-carbon products, as suggested by *Ørsted in 2018* [192], Ernst & Young in 2021 [193] and Deloitte in 2022 [194]. More broadly, insights on financial perceptions of domestic hydrogen can enhance research findings on consumer WTP for green technologies and services [195,196], which is a pivotal aspect of forecasting national energy transitions [197].

3.2.2. Consumer engagement with energy markets

Historically, the UK energy market has been dominated by six companies, with British Gas holding the largest market share [198,199]. Five companies[16] have more than 70 % of the total market share, while a newcomer (Octopus Energy) has around 11 % market share [200]. Analysts argue that the profitability of such companies has been consolidated through a 'loyalty penalty', whereby customers loyal to the same supplier remain on expensive default standard variable tariffs [201,202]. Consequently, around 50 % of households, typically those in fuel poverty or facing conditions of fuel stress, are significantly overcharged for their energy usage [203,204].

Ofgem [205] have surveyed consumer perceptions of the UK energy market over several annual quarters. The most recent surveys have coincided with the ongoing global gas crisis and subsequent changes to the EPC, which continue to impact energy affordability, market stability and consumer engagement [206,207]. Critically, in the third quarter of 2022,[17] it was reported that 53 % of consumers had affordability concerns, compared to 51 % in the first quarter of the year [207]. Moreover, across twelve surveys conducted since the third quarter of 2019, there are persistent trends of decreased satisfaction and increased dissatisfaction among consumers, as depicted in Figs. 3 and 4.

In terms of net satisfaction,[18] the mean peak can be traced to the second quarter of 2020 ($M = 77.1$ %), while the most recent survey (Q3 2022) has seen a decline of over 12 % ($M = 65.0$ %), compared to a mean of 73.6 % for the period ($SD = 4.1$). Mirroring these trends, levels of net dissatisfaction have more than doubled since the third quarter of 2019 ($M = 7.4$ %), reaching a historic high of 15.0 % three years later.[19] Declines in confidence and satisfaction have proved especially pronounced in relation to ease of contacting energy companies, and comparing energy suppliers and prices.

Overall, data collected by Ofgem [164,204,207] shows that vulnerable consumers remain less engaged, whereas owner occupiers, mid-ages, and higher social grades are more prone to switching energy supplier. Consumers with a propensity towards switching energy suppliers also feel more confident about comparing energy deals and making the best choice. By contrast, disengaged consumers are generally more risk-averse when it comes to switching supplier and more likely to prefer larger or better-known suppliers [164,207]. Moreover, vulnerable consumers such as those with a long-term illness or disability are significantly more likely to be dissatisfied with their energy supplier [206,207], emphasising the need for policy prescriptions to address energy vulnerabilities in the UK [135].

Supporting these findings, studies in both the academic [73,208,209] and grey literature [185,210] attest to widespread levels of consumer disengagement with energy markets, especially beyond the main activity of switching tariff or supplier. For example, Spence et al. [211] found that consumers in lower social grades and reliant on prepayment meters were less likely to adopt demand-side management technologies, despite facing affordability challenges. Consequently, this study coincides with an unprecedented period of socio-economic hardship and anxiety, which has negatively impacted satisfaction with energy suppliers and markets across a range of metrics, as examined in Section 5.5.

3.2.3. Technology perceptions and preferences

In addition to financial perceptions and engagement with energy markets, technology perceptions and preferences will influence market acceptance for hydrogen appliances [73]. Mirroring the market for energy suppliers, the boiler manufacturing market is highly oligopolistic, with four companies having most of the market share [105,106]. In parallel, this group is leading the charge to develop hydrogen-ready appliances, which continue to be tested in trials and demonstration projects [29,212]. It follows that consumers would be selecting their hydrogen appliances from existing companies such as Worcester Bosch [213,214], unless new companies were to enter the market over time.

Given that the average gas boiler is usually replaced after about 12 years [183,215], domestic hydrogen adoption may be partly driven by brand familiarity [73], as is the case for other consumer durables such as heating, ventilation, and air-conditioning appliances [216]. For example, Seitz et al. [216] found that consumers were willing to spend more on an air-conditioner with a reputation for quality, which was positively associated with an established brand name. Analysing purchasing trends in the Taiwanese refrigerator market, Lin et al. [217] found that the drivers of repeat purchase among consumers were "ease of use, innovative design, design excellence, and extra features,"

[14] Additionally, German, Spanish, and Italian respondents had a significantly higher WTP than participants in the UK.

[15] Notably, hydrogen was reported to be a much less popular option across all countries. Only 11 % of respondents preferred a switch to hydrogen compared to 32 % choosing solar heating [89].

[16] British Gas, E.ON, EDF, ScottishPower and OVO.

[17] Data was collected using a mixed-methods approach, consisting of computer-assisted web-interviewing (N = 3082) and computer-assisted telephone interviewing (N = 150) between July and August 2022. No data was collected during the second quarter of 2022.

[18] Ofgem employed the following five-point Likert scale in their surveys: Very satisfied; Satisfied; Neither satisfied nor dissatisfied; Dissatisfied; Very dissatisfied. A sixth option, 'Unsure' is also included.

[19] Compared to a mean of 9.5 % for the period ($SD = 2.5$).

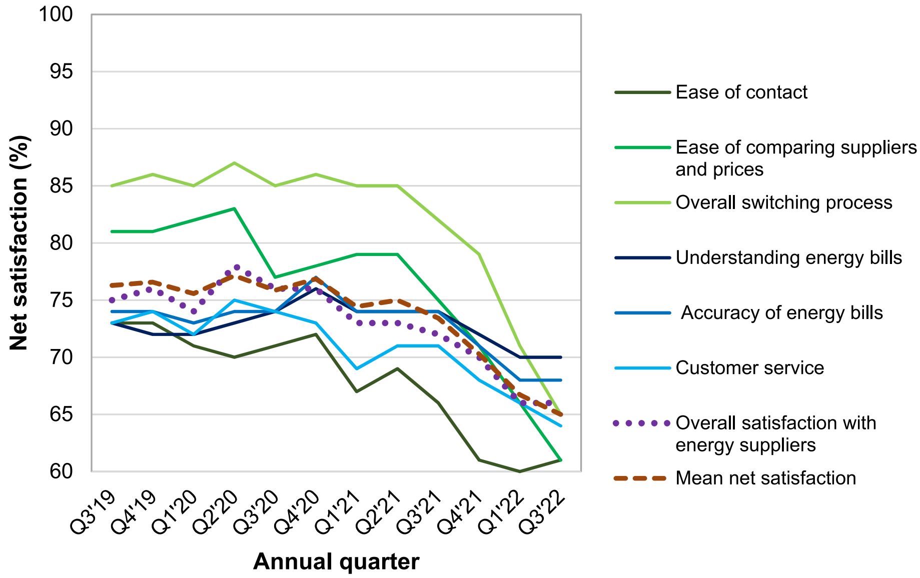

Fig. 3. Net satisfaction with energy supplier and markets. Authors' design based on [206,207].

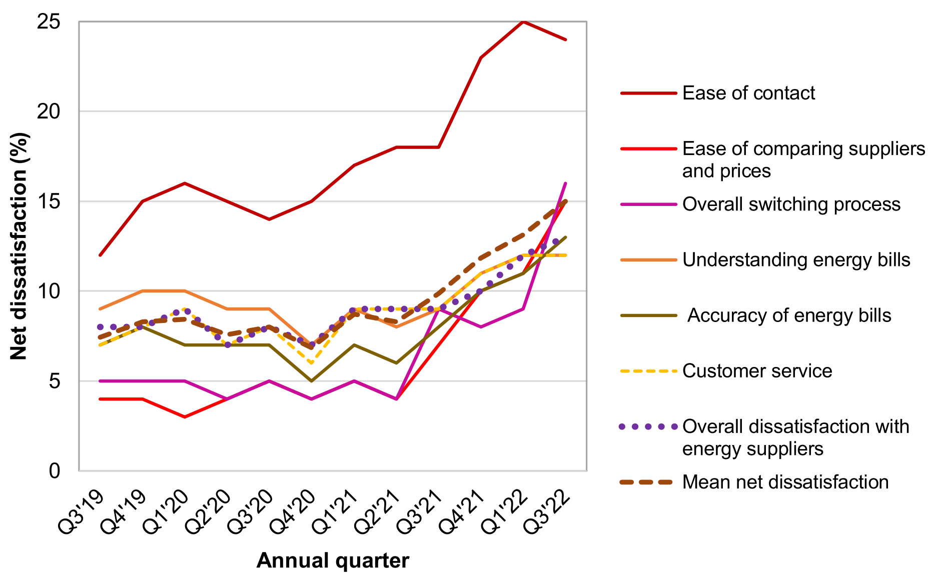

Fig. 4. Net dissatisfaction with energy suppliers and markets. Authors' design based on [206,207].

whereas Bayus [218] highlighted the importance of product performance for brand loyalty towards consumer durable products.[20] Alternatively, in addition to consumer dissatisfaction, limited diversity in terms of models and sizes may trigger brand switching [217].

Energy technology acceptance, particularly for smart homes devices and appliances, is higher when benefits are easily recognisable [219]. However, identifying cost-effective and energy-efficient appliances remains a challenging proposition for most consumers [220]. Additionally, when health and safety issues arise or are otherwise anticipated, consumer acceptance is likely to waver [219]. Concerns around hazards and risks could impede positive perceptions of hydrogen technologies [176,221,222], irrespective of their actual safety performance.

Counteracting these acceptance barriers [24], market reports suggest UK consumers have a growing preference for embracing sustainability [194] and adopting renewable or low-carbon energy products across a wide range of goods and services [192]. It follows that communicating the potential environmental benefits of hydrogen appliances may prove critical to encouraging market uptake and building social acceptance [73,223].[21] Consequently, for some consumers, technology perceptions and preferences will interact with knowledge and awareness of environmental impacts [75]. Accounting for these dynamics, Section 5.6 explores consumer preferences for appliance brands and models in the context of hydrogen homes.

[20] While 'brand equity' can be defined in terms of the "added value with which a given brand endows a product" [389], 'consumer-based brand equity' is composed of brand awareness and image [390] which may promote brand loyalty [216].

[21] However, the emissions intensity of blue hydrogen [391–393] could undermine its role as a transitional fuel [38,394] towards realising a green hydrogen economy [395,396], while green hydrogen is not without its sustainability challenges [397] including GHG emissions risks from leakage [398].

3.3. Community acceptance: spatial dynamics and energy justice

Community acceptance for domestic hydrogen will be influenced primarily by public perceptions of perceived benefits, risks, and costs, which relate to economic, social, and environmental impacts [73,75]. More precisely, community acceptance is configured by perceptions of distributional, procedural, and recognition justice [224,225], which reflect equity impacts at the local level [226,227]. Accordingly, in a recent review, Gordon et al. [73] explored community acceptance in respect to the "spatial dynamics of hydrogen communities" and potential energy justice impacts.

The importance of regional industrial clusters and innovation systems has been identified in the context of hydrogen and fuel cell development across Europe [228]. Madsen and Andersen [228] highlighted the role of geography in establishing hydrogen hubs and engaging stakeholders in the UK Midlands and parts of Wales, finding an association between high activity in fuel cell development and innovativeness. Furthermore, industrial agglomeration around the hydrogen economy has been shown to support synergistic benefits [228] and public trust [229].

The geographical dynamics of the UK hydrogen transition are strongly dictated by activities around large industrial clusters [230], which contribute significantly to national GHG emissions [114,231, 232].[22] Within such areas, large-scale facilities for a range of energy-intensive activities such as electricity generation and distribution, oil refining, manufacturing and distribution are co-located [114]. Adopting this terminology, a hydrogen cluster can be defined as follows:

A geographic region where one large or a co-operative of smaller potential demand exists or alternatively as site which is advantaged through access to land and infrastructure such that it has the potential to become a hydrogen hub and distribute hydrogen to outlying customers [233].

To date, two hydrogen clusters have received Track-1 government funding as part of the Carbon Capture, Utilisation and Storage (CCUS) Cluster Sequencing Process [234]. The HyNet industrial cluster covering Merseyside and North Wales [235], and the East Coast Cluster linking Teesside and the Humber [115] received approval, while the Scottish Cluster (Projects Acorn Hydrogen and Fife Hydrogen Hub) was announced as a reserve [236].[23] Consequently, the emerging spatial dynamics [237] of the domestic hydrogen transition revolve around coupling heat decarbonisation to industrial strategy [29,51,101].

Given that 23 million UK households rely on natural gas for heating [110], while around four million remain unconnected to the gas grid [238], the transition to hydrogen homes would entail a significant degree of spatial exclusivity [73,75]. Many parts of the country, both grid-connected and off-grid, are strongly characterised by "uneven economic and social geographies" [176], which poses an imminent risk to proliferating fuel poverty [71,135]. There is an imminent risk of exacerbating energy inequities should off-grid properties lag in the decarbonisation timeline [72,99]. These disparities could compound the difficulty of securing a socially acceptable and efficient decarbonisation pathway [75], aligned to the principles of energy justice and a 'just transition' [239–242].

Motivated by a similar rationale, Upham et al. [243] recently developed an integrated framework engaging with justice issues linked to industrial decarbonisation, wherein community-based planning and community capacity enhancement are important aspects of social acceptance. Furthermore, Devine-Wright [114] has explored the relationship between reinhabiting industrial sites and community acceptance, reflecting the need to understand interactions between siting decisions and public engagement. Interestingly, Cowell [237] found many UK gas projects have successfully reinhabited sites of former fossil fuel power stations, whereby developers mobilised arguments around the net environmental benefits of such projects, while encountering minimal local resistance about landscape impacts.

At present, UK studies suggest mixed perspectives regarding the community impacts of domestic hydrogen [65,78,168]. Van Alstine and Bastin [168] reported moderate to high levels of local acceptance for hydrogen stimulating a green economy in Leeds, but also noted high levels of uncertainty as to whether hydrogen technologies would benefit local communities, as opposed to large businesses ($M = 3.4$).[24] Relatedly, Scott and Powells [65] noted strong concerns over socio-economic risks and distributional injustice among survey respondents in the North of England, while focus group respondents from Manchester and Birmingham expressed reservations over exacerbating energy vulnerabilities [78], which has also been echoed in the Australian context [72].

Given the potential synergies between industrial and residential sectors in the context of the UK hydrogen transition (see Section 1), community acceptance should be examined in relation to place-specific dynamics [75,114,244]. While some initial insights on community acceptance have been generated, few follow-up studies have been conducted to validate pre-COVID 19 results. Moreover, there is limited evidence regarding the equity aspects of the hydrogen switchover [72, 78,176]. Similarly, efforts to explore the spatial dynamics [245–247] and justice implications [224,248,249] of the energy transition continue to lag [75]. To help reverse this trend, Sections 5.7 and 5.8 engage with community acceptance through the lens of perceived benefits, costs and risks, in addition to spatial dynamics and energy justice.

3.4. Household acceptance: temporary disconnection from the gas grid

Should the domestic hydrogen transition receive policy support in the upcoming years [29], the switchover process would require households to be temporarily disconnected from the gas grid while appliances are changed or upgraded [250]. Disruption levels will depend on the duration of disconnection, which may range from several hours to a few days [78,162,185].

A nationally representative UK survey ($N = 2000$) conducted by the Decarbonised Gas Alliance [162] provides the only available quantitative evidence on this aspect, finding 39 % of respondents were 'unconcerned' about being without gas 'for a few days in summer' compared to 34 % expressing 'concern'. Additionally, the researchers [162] conducted four focus groups ($N = 32$) split between the North of England and Greater London, which suggested concerns over short-term disruption could be mitigated and appeased in most cases. While the prospect of disconnection raised some initial concerns, respondents were broadly satisfied provided solutions such as meal vouchers, bottled gas or financial compensation could be offered [162].

In a study conducted with four focus groups ($N = 39$), representing consumers from different housing segments in Manchester and Birmingham, Grey et al. [78] specified a hypothetical scenario in which 300 homes would be switched to hydrogen in the summer over a three-to-four-day period. Notably, participants emphasised that heating and hot water would still be needed during the summer, while questioning the feasibilty of completing the switchover in less than four days

[22] It is estimated that the industrial sector is responsible for approximately 16 % of total UK CO_2 emissions [399], with the country's six largest industrial clusters (Humberside, South Wales, Grangemouth, Teesside, Merseyside, and Southampton) contributing around two-thirds of national industrial emissions [232]. Additionally, the Thames Estuary region emits around 12 million tonnes of carbon dioxide equivalent per year ($MtCO_2$/year), which is almost on par with Humberside (~12.4 $MtCO_2$/year) [232].

[23] In 2020, the Thames Estuary Growth Board also launched its 'Green Blue' action plan [400] and 'hydrogen route map' to accelerate its decarbonisation agenda for industry and transport, both on land and water [233]. The 2022 Capital Hydrogen programme also comprises a series of projects for the London and Southeast region over the next 15–20 years [401].

[24] As measured on a seven-point Likert scale (7 = Strongly agree).

[78]. Other complaints were voiced over the disruption to home workers, alongside broader impacts to living arrangement during the switchover period [78]. Conversely, when conducting deliberative workshops, Fylan et al. [185] reported an underlying assumption that UK respondents expected the disconnection period to last a few hours, which resulted in minimal qualitative evidence on tolerance limits.

Across the few studies conducted in the UK, one consistent finding in the need to safeguard vulnerable parts of society during the switchover period [78,162,185], which is a concurrent theme in Australian research [72]. However, in addition to the lack of both quantitative and qualitative evidence on perceptions regarding temporary disconnection, the referenced studies date back to 2019–20. In response, Section 5.9 contributes up-to-date and in-depth findings on this dimension of household acceptance, which may help steer strategic decisions regarding the acceptable duration of the switchover process, while accounting for perceptions of individual risks and associated energy vulnerabilities.

4. Methodology

4.1. Focus group design and sample characteristics

This research involved carrying out 10 semi-structed online focus groups between February and April 2022 using the Zoom platform [251]. Based on prior research on early adoption [252,253], environmental engagement [254–256], low-carbon developments in industrial areas [115,234,235], and fuel poverty impacts [257–259], participants were purposively selected to represent a range of different consumer segments, as described in Fig. 5. In addition to enabling opportunities for comparative analysis, this approach was implemented to account for the potential impact of citizens interested in community renewable energy (FG1, $N = 5$; FG2, $N = 6$), consumers with a propensity to be early adopters (FG3, $N = 3$; FG9, $N = 8$), residents engaged in environmental issues (FG4, $N = 3$ and FG8, $N = 9$), people living in industrial towns (FG5, $N = 5$), households facing fuel poverty pressures (FG6, $N = 3$ and FG10, $N = 10$), as well as a 'baseline group' (FG7, $N = 6$) which excluded these variables.

Three modes of recruitment were employed by the research team to secure participants for the focus groups: networking[25] with members of the local community in Marston Moretaine, Bedfordshire (FG1 and FG2); employing a market research company (FG3, FG4, FG5, FG6 and FG7); and through outreach on social media platforms (FG8, FG9 and FG10). To support the recruitment process, five Qualtrics surveys were designed with a series of specific filters matching these requirements, in addition to context-specific filters described in Ref. [260], and various

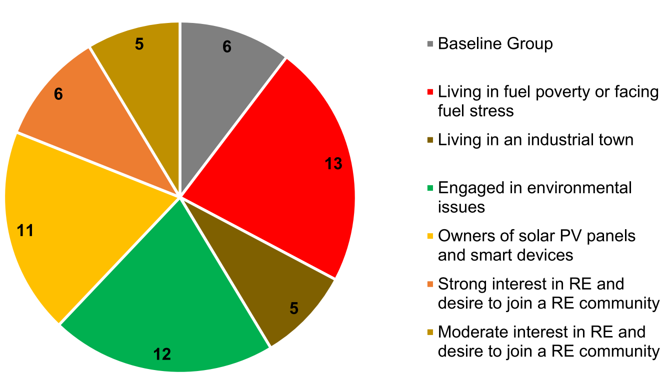

Fig. 5. Distribution of consumer sub-groups.

[25] With the Commercial Director of the Marston Vale Millennium Country Park, members of the Parish Council and local online groups.

quotas on socio-demographic variables (see Supplementary Note 1). While the final sample ($N = 58$) represented several parts of the UK population, some locations such as Wales, Scotland, and the Northeast England were underrepresented (see Fig. 6), which should be addressed in subsequent studies. Overall, this study encountered certain limitations[26] in retrieving a fully nationally representative sample, which is an inherent constraint when adopting the focus groups method [135]. However, by including several sub-groups, the research design helped neutralise a partial lack of representativeness, while supporting the underlying objective to ensure diversity among participants and scope for representing multiple perspectives.

4.2. Focus group format and information provision materials

Based on literature review findings [24,73,75], the research team established a topic guide to motivate discussion on aspects of socio-political, market, community, and household acceptance. Each focus group lasted around 90 min and was moderated by the lead author, with support from co-authors and research colleagues. The same approach and design were maintained throughout each session, supporting consistency in terms of data collection to optimise opportunities for subsequent comparative analysis. In some focus groups, the moderator probed participants with follow-up questions to help extract more nuanced details on their perspectives, while at other times participants required minimal prompting and led the discussion in the first half of the focus group engaged with consumer preferences for cooking and heating technologies as reported in Ref. [260], perspectives on climate change, energy and environmental issues as documented in Ref. [261], and attitudes towards the UK Hydrogen Strategy and production pathways which are examined in Ref. [262]. The second half of the discussion focused on the themes tackled within this analysis, following questions reported in Table 1. To support the discussion, a combination of information provision materials were employed, including two short videos and animated PowerPoint slides (see Figs. 7 and 8).

Leading into the discussion on public trust, participants viewed a Channel 5 News video segment[27] aired on August 17, 2021 to mark the release of the UK Hydrogen Strategy [29]. Following discussion of the video, which included a mix of government, industry, and scientific perspectives on hydrogen, the moderator shared a clip from Northern Gas Networks on the H21 Project [263].[28] This segment provided participants with a visual representation of hydrogen home appliances, as transmitted via the HyStreet demonstration site located at Spadeadam, Northumberland [264]. The video content was restricted to a series of short subtitles, which minimised the potential for bias or emotional cues (see Supplementary Note 2).

Next, the moderator shared an animated PowerPoint slide illustrating the key actors and stakeholders within the UK hydrogen landscape. The slide firstly showed a group of houses and energy companies to illustrate how a given street may have multiple energy suppliers. Next, Fig. 7 presented the four GDNOs responsible for managing the UK grid. Thereafter, interactions between government, industry, and the independent regulator (i.e. Ofgem) were outlined, before highlighting the links between academia and business consortiums, and finally the role of leading boiler manufacturers within the Energy & Utilities Alliance (EUA). Subsequently, participants reflected on their trust levels in different actors and stakeholders, and were prompted to justify their

[26] The sample was broadly nationally representative in terms of gender (slight over-representation of males); loosely nationally representative of housing type and marginally representative of housing type; over-represented by 26–35-year-olds and under–represented by 65+; and had a somewhat higher average number of occupants per household (3.1) compared to the national average (2.4).

[27] https://www.youtube.com/watch?v=g-VpyglBhrI.

[28] https://www.youtube.com/watch?v=CtAzCv5Sc48.

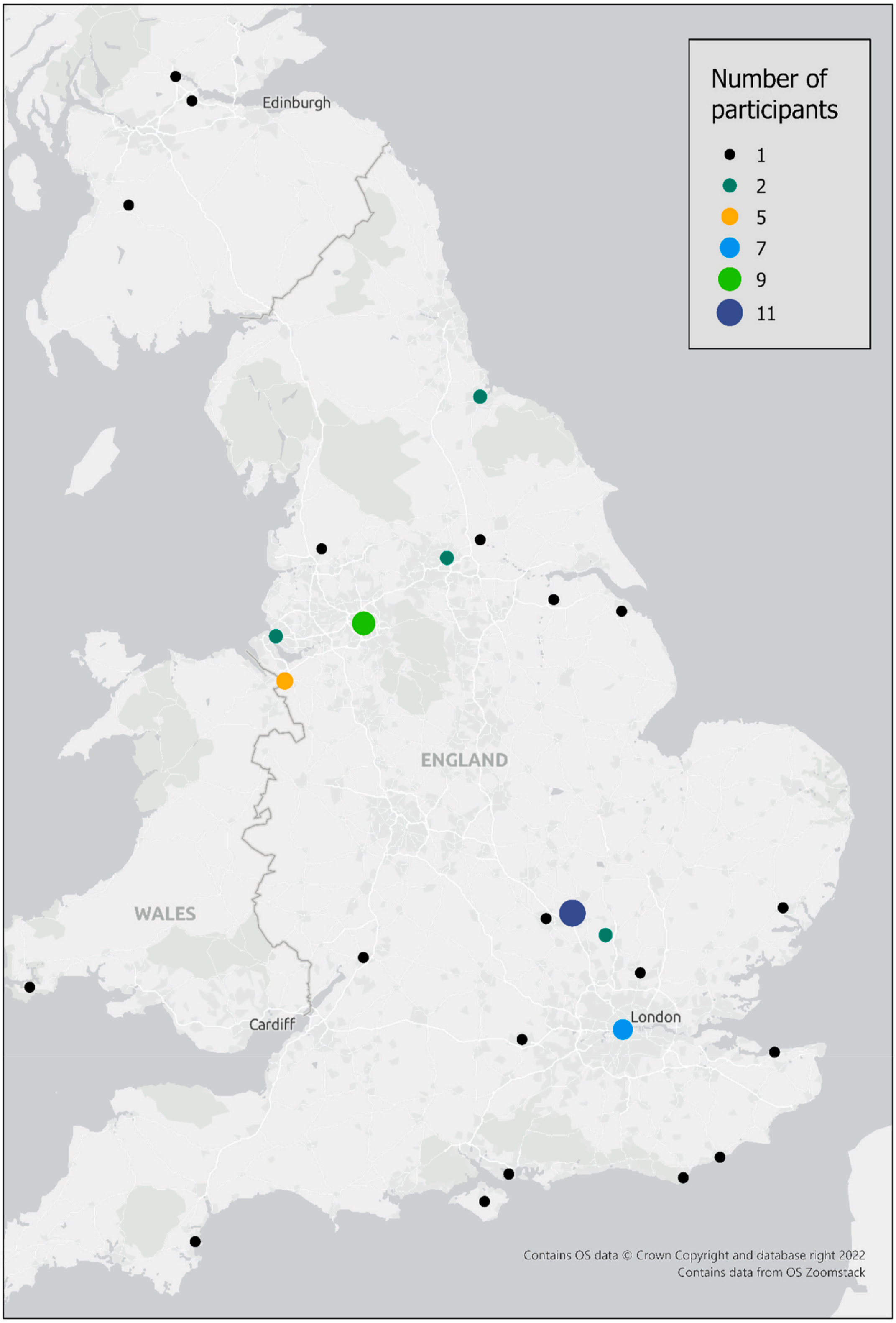

Fig. 6. Location of focus group participants. This map is also included in Supplementary materials by the authors in Ref. [260].

views.

Finally, to help frame the discussion on community acceptance, participants viewed an animated PowerPoint slide illustrating the spatial dynamics of the UK hydrogen transition. The materials informed participants about the location of past and ongoing hydrogen trials and demonstration projects (black dots), the first cities and towns forecasted as potential candidates for deploying hydrogen homes (white dots), and the location of the HyNet and East Coast Cluster projects (red stars). Participants were also provided with additional information about the role of GDNOs and informed about hydrogen activities in Fife, east-central Scotland [265,266].

Table 1
Overview of acceptance dimensions, themes and questions.

Acceptance dimension	Themes	Questions
Socio-political	Trust levels in key actors and stakeholders of the UK hydrogen transition	• How do you feel about trusting the main actors and stakeholders of the hydrogen transition? • How do you feel about having a choice when it comes to switching to hydrogen?
Market acceptance (1)	Choices and decisions regarding energy suppliers, appliance brands and models	• Has anyone changed their energy supplier in the last few years or more recently? • How would you go about choosing your energy supplier if using hydrogen? • How do you feel about having a choice about appliance brand and model?
Market acceptance (2)	Financial perceptions of the purchasing, running and maintenance of domestic cooking and heating technologies	• How do you think the cost of hydrogen appliances should compare to natural gas appliances? • How do you think energy bills for hydrogen should compare to natural gas? • What cost impacts do you expect when it comes to maintenance of your appliances?
Community acceptance	Community benefits, costs and risks of the hydrogen switchover	• What do you see as the potential benefits of hydrogen for your local community? • What do you see as the potential costs or risks of hydrogen for your local community? • How do you feel about having a choice when it comes to switching to hydrogen?
Household acceptance	The disruptive impacts of hydrogen homes and energy vulnerabilities	• How long would you tolerate being temporarily disconnected from the gas grid during the switchover? • How do you feel about engineers and technicians having access to your home during the switchover?

4.3. *Integrated mixed-methods multigroup analysis*

In comparison to strictly qualitative or quantitative analysis [267–269], mixed-methods research offers a more complete approach for engaging with complex societal issues [270]. Traditionally, mixed-methods research is conducted via separate qualitative and quantitative stages prior to integration [269,271], however, a convergent method (i.e. bidirectional approach) [272] can also be achieved within a single stage of data collection to merge both 'strands' of evidence more directly [270]. Through this approach, integrated mixed-methods analysis [273] can support 'narrative weaving' [269, 274]; whereby qualitative and quantitative results are merged thematically [271] to enhance the scope of findings [273].

Focus groups provide a powerful research method for conducting qualitative social science research [270,275], with strong applicability for examining public acceptance of emerging energy technologies [276, 277] and attitudes toward the energy transition [278,279]. Notably, Sandri et al. [72] and Smith et al. [256] also employed focus groups to extract insights on different aspects of hydrogen acceptance. Principally, the focus group format supports flexibility and openness [276], which may reveal important insights otherwise overlooked in quantitative studies. Consequently, the method is recommended for generating deep insights [280,281] on novel topics [276] such as hydrogen homes [262]. However, the risk of potential bias due to the role of the moderator [282] and nature of group-specific dynamics [283] should be recognised, while the online format entails the limitation of digital exclusion [284].

By pooling multiple perspectives and facilitating dynamic group interactions [281,285,286], focus group data can also support a multigroup analysis [287,288], whereby areas of convergence and divergence between participants are thoroughly examined [260,289,290]. While multigroup analysis is usually reserved for analysing large-sample survey data [291–293], this study demonstrates the efficacy of adopting the approach when extracting quantitative insights from qualitative data [294]; equating to an integrated mixed-methods, multigroup analysis, which reflects the end goal in Fig. 9.

Aligning with other studies on energy acceptance [295,296] including hydrogen homes [72], the audio recordings were transcribed and inductively coded for each focus group using NVivo 12 qualitative data analysis software [297]. This approach facilitated an inclusive assessment of all available codes within the dataset [298,299] to support a rigorous combination of thematic and content analysis [300]. Firstly, thematic analysis [301] was undertaken by ordering and analysing consumer responses [302] to help capture the emerging narrative on hydrogen acceptance [72,303]. Secondly, analysing the themes and quantifying these outputs revealed areas of convergence and divergence [302] to enable an inductively-driven, comparative analysis [304–306]. To support narrative weaving throughout Section 5, a combination of illustrative statements and summary tables are provided to reflect the main themes and critical points [135,307].

5. Acceptance dynamics of the domestic hydrogen transition

5.1. *Public trust in the government*

Trust levels in the UK government varied notably between certain focus groups, revealing a tendency towards scepticism and mistrust in many cases (see Supplementary Note 3). For example, one participant was pessimistic about the future: "*I'm not sure I trust this government a lot to take things forward for the next 10 to 15 years. Will this just be another flash in the pan? I need to see action behind the talk from the government and serious investment*" (FG2:1). In some cases, respondents positioned the government as potentially more trustworthy than other entities: "*I'd hope that the government would be impartial, whereas British Gas or other private companies would obviously have shareholders. I would hope the government would at least want to do the right thing*" (FG7:2). However, other respondents countered this viewpoint: "*the government needs to work on building trust. I would trust the energy companies more than the government*" (FG10:8). By contrast, a minority of participants expressed complete trust in the government and industry, "*the companies, the suppliers and the government, we have 100 % trust and will go with them, especially because it's good for the environment, the future and the earth*" (FG9:10).

In total, one-third of respondents ($N = 19$) discussed trust in the central government, wherein low trust ($N = 10$) prevailed as the most frequent perception, followed by high trust ($N = 6$), and partial trust ($N = 3$). While findings at the sample level serve to emphasise a tendency towards mistrust, it is also noteworthy that specific sub-groups demonstrated clear response patterns, as reflected in Fig. 10. At the positive end of the trust spectrum, owners of solar PV panels and smart devices (FG3 and FG9) expressed unequivocal confidence in the government. By contrast, participants interested in joining a RE community (FG2) or actively engaged in environmental issues (FG4 and FG8) framed their lack of trust around past negative experiences with UK energy policies. For example, one respondent referenced the high cost of heat pumps, problems with solar feed-in tariffs, lack of electric vehicle infrastructure and "*getting stung by diesel cars in 2009*" (FG2:3).

It may be inferred that acquiring solar PV panels and smart devices

Fig. 7. Animated PowerPoint slide depicting key actors and stakeholders within the UK hydrogen landscape. The image is considered a selective representation accounting for active parties as of February 2022, as opposed to an exhaustive representation of the UK hydrogen landscape.

Fig. 8. Animated PowerPoint slide illustrating the spatial dynamics of the UK domestic hydrogen transition. Scotland was partially cut off in the animated slide to enable a clear resolution. The original version of the central map is presented in Ref. [75] where Scotland is fully visible.

instils a stronger sense of confidence in energy policies, which may motivate similar investments. By contrast, aspirations for joining a RE community link to the desire for energy independence, which may be associated with mistrust in the government. Interestingly, baseline respondents (FG7) were equally split between trust categories, while fuel poor/fuel stressed participants (FG6 and FG10) were slightly skewed towards the negative end of the spectrum, which likely reflects their disillusionment with recent government policies.

5.2. Public trust in key actors and stakeholders

In some instances, participants drew more explicit comparisons to other key actors and stakeholders in conveying their trust levels (see Supplementary Note 4). Consistent with international research [153, 188], strong concerns over the profit motives of energy companies and other private organisations surfaced in multiple focus groups (i.e. FG2, FG3, FG4, FG7, FG8). For example, one respondent drew wide approval from other participants when critiquing corporate taxation rates and the profit margins of a major oil producer, "*the government needs to tax it*

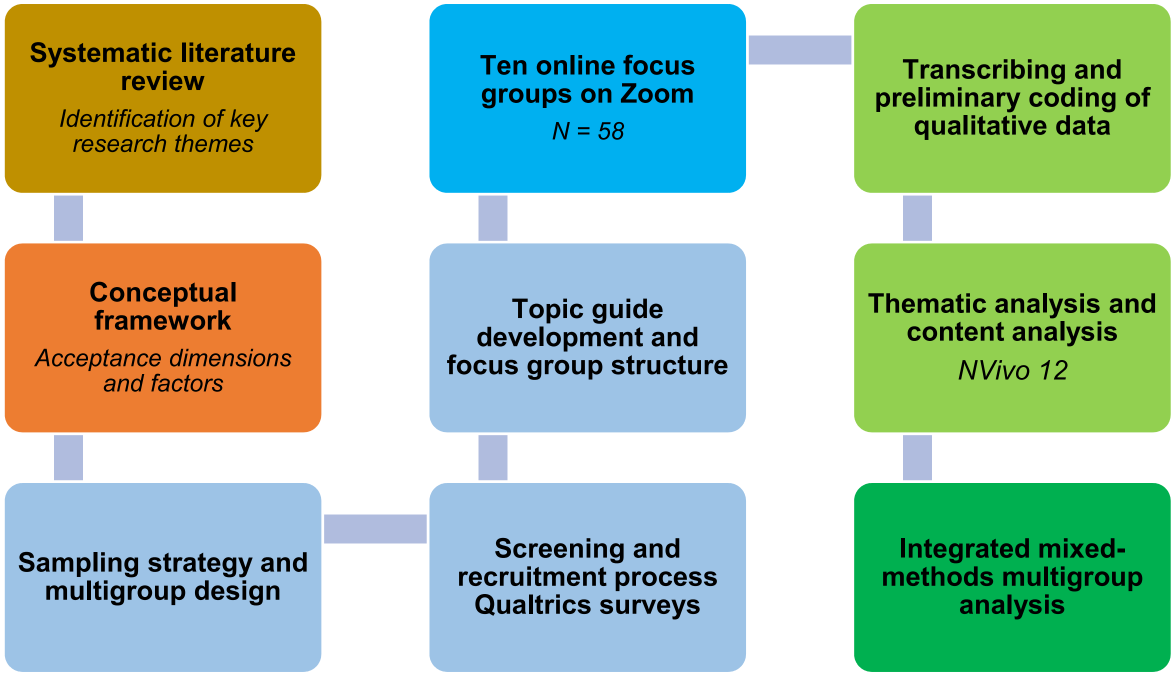

Fig. 9. Methodological approach and research stages.

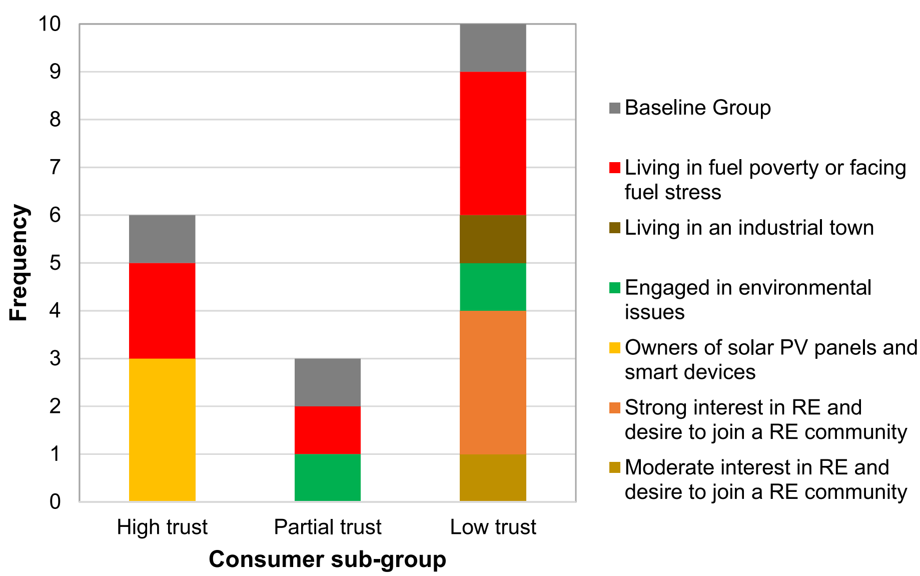

Fig. 10. Public trust levels in the UK government.

because all our gas bills have just doubled, yet BP has just announced £9 billion profit … how about they make £1 billion profit, and our bills stay the same as they were" (FG2:3). By contrast, participants saw Ofgem as a trustworthy entity and were generally confident in information provided by universities and research organisations, which has been found in other studies [163,308].

One respondent (FG8:3) with extensive experience working in community-led housing in the Northeast of England expounded on the "*root of trust*" concerning the UK hydrogen transition:

> "*… well, where is the power? With the people? No! We are being guided by having to put our trust in industry and government and the institutions to come up with the right solutions for the right reasons. Going back to the root of trust and that landscape … we would generally think that the academic institutions would be the most objective and reliable, and I think they are. I'm not disputing it*" (FG8:3).

When public trust wavers, social friction towards the hydrogen economy is more likely [157], which may counteract socio-political acceptance [309] for residential decarbonisation [310].

In some cases, participants also took a macro-view of the UK hydrogen landscape as presented to them in Fig. 7, which drew largely polarising perspectives, as described in Table 2. Most respondents were reassured by the range of actors, while others perceived multiple actor-networks as a potential barrier to implementing meaningful and coordinated action. Notably, a business manager working in the finance sector (FG1:1) viewed the evolving direction of the hydrogen landscape positively, owing to more inclusiveness and stakeholder engagement, reflecting a potential shift towards increased procedural and

Table 2
Perceptions of the macro-environment and emerging hydrogen landscape.

Participant	Illustrative statements
FG1:1	• *At the minute, people investing in ethical and sustainably sourced economics is becoming more and more of a thing, so it's going to get more and more backing as more people are investing into it. It won't just be down to the big wigs in Parliament and the mass stakeholders anymore. It is becoming more sociable and more conscious of society to invest in these areas rather than just the big corporations that are guaranteed to make money. So, it's going to become bigger, and I think not just bigger, but more secure for people going into it because it is getting more backing from Joe Bloggs.*
FG1:5	• *It's very good to see there are brands you recognise and also that there are so many stakeholders involved.*
FG3:3	• *Well, I guess there's a lot of people involved which could complicate things. That could be a problem (FG3:1 responds "Yes")*
FG7:4	• *One problem with the set-up here as portrayed is there is a myriad of organisations involved and that seems to be a recipe for doing nothing!*
FG8:2	• *There are simply too many parties involved for us to understand all this. I used to work for Transco who have now been swallowed up. It's a minefield because you can't actually change the choice of the person who provides your gas piping. You can only change your energy provider in name and label. It's not really changing your supplier.*
FG9:1	• *I think there's quite a large blend of experts, whether it's from companies or manufacturers, government, or utility companies. It seems quite a varied mix which makes me feel better. It's not all coming from the government, or it's not all coming from companies with vested interests.*
FG9:2	• *Now, those organisations … have significant responsibility, legally as well as ethically, and for that reason they have experts … to ensure that things like the [lack of] smell and the concerns that were raised earlier get addressed. So, it's a natural progression and I have 100 % confidence that it can be done safely and ethically.*

distributional justice. However, other respondents cited concerns over potential conflict and inaction among "*a myriad of organisations*" (FG7:4).

Interestingly, there were also objections to privatisation, with one respondent commenting that "*nationalisation is also a good way to go to help the people*," (FG8:7), while another participant elaborated further:

> "*I feel the energy system should be controlled and organised by the government, with the government having total control over it and other stakeholders having just a minimal role in the discussion and actions regarding the energy system*" (FG9:6).

Such perspectives are timely, following a call from the Trade Union Congress (TUC)[29] for government reforms to make the "Big Five" energy companies publicly owned [200,201]. The TUC advocates for a 'social pricing structure' to enable affordable prices for basic energy services, in line with other European countries [200]. Speaking to this issue, one respondent came to the following conclusion: "*the government should not allow the costs to be passed on to the consumer. We all have to play our part [in net zero], but none of us can afford to if it's all on our shoulders*" (FG2:3).

The TUC also cites the past transition from town gas to natural gas [119,311] as an exemplar of the need for coordinated central planning, when it comes to enacting a successful, large-scale domestic energy transition [200]. Reflecting these pressures, the UK government launched the Review of Electricity Market Arrangements (REMA) between July and October 2022 [312]. The consultation aimed to "identify reforms needed to transition to a decarbonised, cost effective and secure electricity system" [313], which may include decoupling electricity markets from the gas price [314]. These ongoing developments reflect the extent to which public trust in both the government and industry will shape the emerging contours of the hydrogen transition, alongside wider prospects for reaching net zero.

5.3. Perceptions of purchasing costs

Purchasing a new gas boiler is a highly context-specific decision which is often triggered by system breakdown, or usually delayed until the appliance reaches the end of its lifespan (i.e. 12–15 years), especially for low-income earners [183]. Absent of environmental pressures and forthcoming regulations, it follows that a large proportion of the UK housing stock could feasibly continue using their current boiler into the mid-2030s. Having recently replaced their faulty boiler, a solar PV owner reflected this reality: "*The whole question of purchasing costs depends on whether the appliance needs replacing or not … if you have a brand new natural gas boiler, you are not going to want to spend a penny*" (FG9:2).

Relatedly, it was stressed how the lifetime of hydrogen appliances should be "*at least 10 to 15 years, to match the reliability of current gas boilers*" (FG3:1). Having moved to a new build house where the boiler "*is probably the most recent spec,*" one participant further explained how an incentive would be needed, otherwise the changeover "*wouldn't be very cost-effective*" (FG5:2). Across the sample, several participants cited the need for subsidies, incentives, or other government schemes to motivate and facilitate the purchase of hydrogen appliances, as reported in Table 3. Furthermore, one respondent linked the domestic hydrogen transition to intergenerational justice [315,316] by drawing parallels between decarbonisation and the public health, "*it's like health, the government need to heavily subsidise this now, otherwise our kids and their kids will be paying for it*" (FG2:3).

Ultimately, it was admitted that "*until you know the economics of it and how much you are going to save, it's hard to say … economically it's unclear, we can't say*" (FG7:1). Additionally, uncertainties in weighing up cost and performance factors were underlined, which could stifle decision-making and consumer uptake if addressed inadequately:

> "*I don't know … if there may be a price hike like when they brought in electric cars like Tesla … it depends about cost-benefit analysis doesn't it? If you are going to pay more and get high quality longevity, then maybe yes. But if there are no sort of guarantees on that, then maybe no. There are a lot of things to weigh up*" (FG4:1).

In addition to referencing the price of electric cars and the capital costs of solar panels, several participants framed their response in relation to the current costs of heat pumps and the Boiler Upgrade Scheme [317], which they saw as too high and insufficient, respectively.[30] However, only two participants (both solar PV owners), shared

Table 3
Consumer perceptions of government support for domestic hydrogen adoption.

Participant	Illustrative statements
FG3:2	• *If they [hydrogen appliances] are a lot more expensive, then people will probably not want them. I can understand they won't be cheap because they are new and because of research and development costs. Maybe there could be something like a green tax benefit for helping the environment in that way.*
FG7:1	• *If you're going to have to spend £6000 to get a new hydrogen boiler, or you have to pay for at least half of it and the rest is a subsidy, then it's not very beneficial to the people that have recently invested in a new gas boiler. I assume there will be some kind of grant in place, so if you've got a ten-to-fifteen-year-old boiler, then it would make sense for you it to change it, and have the government pay towards … they have to assist you.*
FG7:3	• *Decisions will depend on government subsidies which tell you do this please and they dangle the carrot.*
FG9:3	• *An attractive market introductory price would be good … and a long-term deal with potential discount for referrals made to other customers.*

[29] A federation of 48 trade unions representing 5.5 million workers [201].

[30] The Boiler Upgrade Scheme supports households with grants of £5000 or £6000 when switching to an air source heat pump (ASHP) or ground source heat pump (GSHP) [101].

a specific figure regarding their willingness to invest in a hydrogen boiler. Estimates ranged from £3000 (FG9:7) to £5000 (FG9:6) for both purchase and installation. A Scottish participant from a family of engineers lent a more technical perspective, "*I'm not sure that it should cost anymore because it might just be the same sort of structure and design. The technology behind that should be much the same*" (FG5:5). Moreover, one participant expressed a position that may represent much of the society, beyond just the North of England or equivalent socio-economic geographies [176]:

"*I would like the price to stay the same, as I'm not in a position to afford a higher price and I feel this reflects a lot of the UK. If I had the extra money, I would be open to pay more for hydrogen but again there are always other things that you could use your spare cash on*" (FG10:4).

Broadly, respondents communicated three perspectives regarding purchasing costs, which are represented in Fig. 11 (see Supplementary Note 5). The mid-range perspective anticipated hydrogen appliances to be roughly on par with natural gas appliances, or at most, marginally more expensive, while subsidies and incentives like tax benefits should still be in place. Other respondents argued in favour of cheaper appliances to counteract widespread unwillingness or inability to pay and subsequent social resistance. Additionally, several participants anticipated or otherwise accepted that hydrogen appliances will cost more because the technology is new; noting that some people would be willing to pay for environmental benefits, while others would require financial support. Bridging these perspectives, one respondent forecasted potential implications:

"*If it was the same cost then people wouldn't bother with disruption … if it was cheaper than natural gas, then there would be a more positive uptake. But if it was the same price or higher, nobody in their right mind would agree … and there wouldn't be that public adoption*" (FG9:2).

In total, one-third of respondents ($N = 20$)[31] provided reflections on the purchasing costs of hydrogen appliances, with 'cost parity' prevailing as the most frequent response ($N = 10$), followed by 'higher costs' ($N = 7$), while a minority of participants argued that 'lower costs' is a prerequisite of market acceptance ($N = 4$). However, insistence upon lower costs failed to be communicated by fuel stressed respondents, who instead were split between an expectation for cost parity ($N = 3$) and higher costs ($N = 3$). While limited to a small sample size, this pattern draws attention to a potential lack of confidence for tackling fuel poverty through the deployment of hydrogen homes, which is somewhat unsurprising given recent trends in energy markets. In parallel, there are indications that consumers anticipate cost equivalence, which resonates with the recent price promise from boiler manufactures.

5.4. Perceptions of running costs

Although initially asked about purchasing costs, several respondents contextualised their answer by citing running costs. For example, one participant desired "*to know what the impacts of the purchase will be on running costs … is there any payback there*?" (FG5:3). Other participants (FG9:2, FG9:3, FG10:2) shared this feeling and believed reduced energy bills would help justify the purchase a hydrogen appliance. Commenting on the initial stages of the transition and the prospect of early adoption across the North of England, one respondent conveyed a mix of realism and pessimism:

"*If it's going to be more expensive … that's not going to go down well without a proper sort of subsidy from the government. It has to be cheaper or on par, but I can't see that happening. I can't see energy costs going down from where they are at the moment*" (FG9:1).

This statement motivated a follow-up reply arguing against a levy on energy bills and potential grounds for aggravating inequities:

"*I think it's a matter for government and taxation. It shouldn't be a levy on energy bills because that would disproportionately disadvantage those that have a very high energy usage as well as businesses, more so than those that have a really low usage. So, it would have to come from general taxation*" (FG9:2).

Responding to the hope that "*energy bills would be less*" (FG1:3), another respondent stressed the importance of transparency regarding the carbon footprint and environmental impact of hydrogen appliances:

"*… or at the very least, your energy bills would be equal to now. I would be willing to pay the same if it was a green option, but I would need to know that it really is a greener option and that there isn't any hidden CO_2 in the background*" (FG1:1).

Participants grappling with fuel poverty touched upon similar themes, for example, "*I'm all for saving the environment, but at what cost is it going to come for the normal household*?" (FG6:1), and "*… we all want to do our part to help the environment but being green is very expensive … you want to help the planet to thrive but not at a cost of reducing what we already have*" (FG6:2). Furthermore, their fellow participant elaborated how "*everyone's circumstances are different, income and household wise*" and felt that "*paying for the appliance and having to maybe pay higher energy bills initially would be a bit off putting*" (FG6:3). This viewpoint was further verified in reflection of the financial challenges facing younger age groups:

"*I have a 22-year-old son moving out soon and it worries me about how he can start off on the property ladder, if you're trying to pay your bills and your mortgage and you have extra costs for the government's net-zero vision. That worries me a lot. I've already seen my energy bills shoot up*" (FG2:1)

Underlining the far-reaching implications of personal circumstances, a Union representative, tasked with helping people with low incomes to pay their energy bills, communicated the plight of citizens in fuel poverty via the chat box:

"*When the decision really is freeze or starve, there is no money for conversion or for swapping energy supplier, and this is pre- the recent hike … when you have no disposable income at all, the cost to the bank balance overrides all else. In fact, the thought that a change would be mandatory at some point will be one full of anxiety*" (FG8:7).

Overall, most participants expected that running costs would either stay the same or decrease slightly , while several respondents proved unwilling to pay for higher energy bills. However, a minority of respondents had a higher WTP in return for a greener option, underscoring the interactions between market acceptance and environmental perceptions [256,262].

5.5. Perceptions of energy suppliers

To better gauge their experience with and attitudes towards energy companies, participants were asked to confirm if they had previously changed supplier, and to share any relevant details regarding this decision and the process. The rationale for introducing this topic was to ascertain how consumers would feel about potentially changing to a hydrogen-specific provider in the future, and to invite reflections on recent events in UK energy markets. Previously, it has been shown that "widespread consumer disengagement in the energy market remains an obstacle to net-zero ambitions and climate change targets" [73].

Government reports show that a high proportion of UK consumers remain disengaged with energy markets [184], especially in terms of switching energy supplier and tariff [203]. Contradicting the national data, all focus groups proved familiar with recent developments in the UK energy market, and several participants had direct experience of switching energy provider. In most cases, respondents had elected to

[31] One respondent provided a dual perspective (FG5:5).

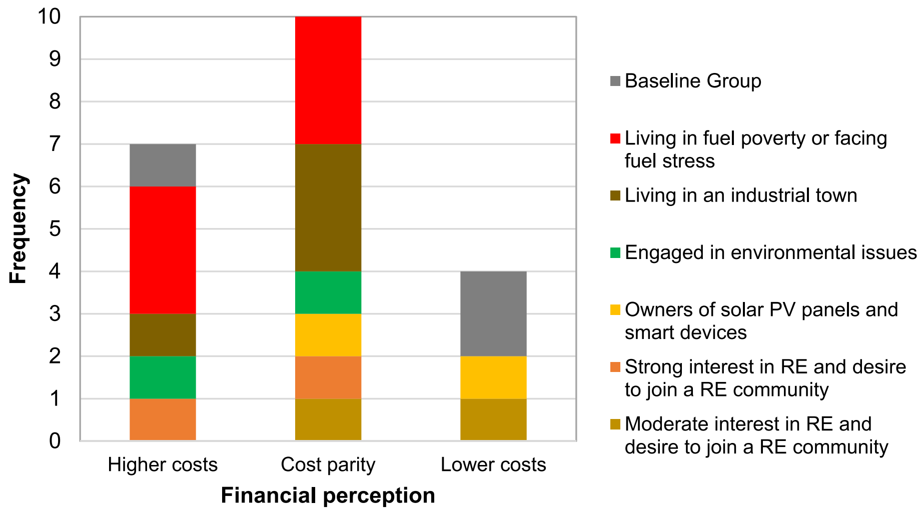

Fig. 11. Consumer perceptions of purchasing costs for hydrogen home appliances.

switch energy provider based on cost benefits, usually doing so on annual basis at minimal inconvenience. At times, the voluntary decision to change had been taken due to poor customer service, as opposed to being "*totally motivated by cost*" (FG1:1). In other instances, respondents had been switched automatically or forced to change provider due to their supplier becoming insolvent.

In total, twelve companies including the traditional 'Big Six'[32] [198,199] were mentioned by various participants spread out across half of the focus groups (FG1:1, FG3:2, FG3:3, FG4:1, FG4:2, FG4:3 FG6:1, FG6:2, FG10:2), while other respondents confirmed past switchovers without mentioning specific details. Consistent with previous studies [89,161,167], a feeling of dissatisfaction prevailed among the sample, revealing a lack of confidence in the credibility of energy providers. One property owner was candid in their criticism and drew widespread agreement from fellow participants: "*We've got two properties and we've been changed over from Npower to E. on, and from First Utility to Shell Energy, and in the past I've used British Gas, and to be honest, in my opinion, they're all as bad as each other*" (FG4:1). Notably, similar perspectives were captured in the study of Sovacool et al. [89], which reported dissatisfaction among UK consumers due to the perceived gross negligence of certain energy companies.

The business models and profit motives [153,165] of one energy provider were called into question as an exemplar, with other participants in the baseline group echoing this viewpoint, "*I was with SSE, then all of a sudden, I've been changed to OVO and they just seem to be making a quick profit and legging it*" (FG7:1). Furthermore, the same respondent elaborated on the importance of market competition:

> "*After what's happened recently with all these energy companies setting up and offering people a really cheap deal and then going under, I suppose you're taking a bit of a gamble. Because if you change to this company that's just set up and it doesn't work, then you probably won't be able to get your gas supply back as quick if it all goes horribly wrong, compared to being with an established company. I think the big issue is competition. If there's only a few companies, then they can put a higher price than if there are 20 companies*" (FG7:1).

To an extent, attitudes towards switching energy supplier reflect the typology developed within the Ofgem Consumer Survey 2020 (update on consumer engagement with energy) [164], which demarcates six specific consumer profiles described in Table 4. Moreover, this study finds that consumer behaviours and preferences may reflect a combination of different profiles, linking to a range of factors such as customer loyalty, price, competition, and reputation (see Supplementary Note 6). While it is instructive to categorise consumers, it is essential to further understand the specific driving factors behind segmentation, which may imply multi-dimensional perspectives.

Considering a prospective market for hydrogen homes appliances, this analysis identifies nine factors which may influence consumer engagement with energy suppliers and the decision to switch provider. In total, 21 respondents (~36 %) provided statements on this topic, mentioning two factors on average ($N = 40$), as illustrated in Fig. 12. Cost savings emerged as the most critical factor ($N = 10$), followed by reputation and reliability ($N = 6$), while factors such as customer service ($N = 4$) and company values and ethics ($N = 3$) had a secondary influence. Notably, some participants expressed their preference for switching to a hydrogen supplier ($N = 5$), which was typically associated with the call for a more competitive market ($N = 4$).

At the sub-group level, participants living in industrial towns and fuel poor respondents accounted for more than half the references to cost savings, with an equal split between the two groups. This association may be attributed to the higher prevalence of socio-economic hardship across industrial heartlands, reflected by a high representation of fuel poor respondents from industrial parts of Manchester and Chester. Insightfully, one member of the industrial towns focus group underscored the relevance of market acceptance within this context, "*that's an important point about consumer choice and who you want to go with if there's only one leading supplier and your stuck with them, whatever the cost or service*" (FG5:1).

5.6. *Preferences for appliance brands and models*

Participants broadly agreed that the hydrogen appliance market should offer well-established and reputable brands to support consumer trust and buy-in, as captured in Fig. 13 (see Supplementary Note 7). Having a wide choice, comparable to the current market for natural gas appliances, was prized by most participants, with one respondent envisioning market diffusion reminiscent of the uptake of smartphones [318,319]:

> "*It may take time, but definitely you should be able to walk into Currys*[33] *or look online and buy these appliances just like you do now. The more*

[32] British Gas, EDF Energy, E. ON, Npower, Scottish Power and SSE. Additionally, participants mentioned Bold Energy, First Utility, OVO Energy, So Energy, Shell Energy and Utilita Energy.

[33] An electrical retailer operating in the UK and Ireland, which specialises in white goods, consumer electronics, computers, and mobile phones.

Table 4
Consumer profiles associated with attitudes towards switching energy supplier.

Consumer profile	Characteristics	Illustrative statements
Happy shoppers	• Confident, trusting and engaged with the energy market • On the lookout for the best deal possible and positive about switching	• *I would switch energy supplier to whoever has the cheapest tariff. There's no loyalty involved (FG7:5).*
Contented conformers	• Broadly happy with the status quo and trusting their supplier • Nervous of change and risk averse, with limited engagement in the energy market and little confidence in or motivation towards switching	• *I've heard some horror stories about people changing energy supplier, so I've stuck with what I know really. Especially because we've had this year or last year where companies were failing because of rising price, you would definitely want to know it's secure (FG1:2).*
Savvy searchers	• Confident, experienced and positive about switching energy supplier • Accustomed to comparing prices across multiple internet sites and finding the best deal	• *I would probably switch because it's something that I do anyway … I would look for a hydrogen supplier … I would look for that compatibility and companies that work well alongside each other. I would be looking for something to simplify everything as much as possible, but also to be affordable as well, and to make things easier (FG6:2).*
Market sceptics	• Very low trust in energy companies • Limited engagement in the energy market and low confidence compared to other markets	• *I think it would be quite good for some new companies to come into the utilities space because at the moment and previously, the current companies, the likes of British Gas and E.ON have quite a bad reputation. So, it might just shake it up a bit if some new providers come in (FG4:1)*
Hassle haters	• Easily deterred by the perceived time, hassle and risks involved in switching supplier • *Partially engaged in the energy market and broadly trusting of suppliers*	• *I would stick to whoever I was with to avoid a double disruption (FG7:4).*
Anxious avoiders	• Low engagement in the energy market and limited ability to switch supplier • Unlikely to allocate time towards seeking a better deal	N/A[a]

[a] Based on recorded responses, this study failed to identify a participant characterised as an 'anxious avoider', however this perspective may have been present among the wider sample.
Source: Authors' design based on [164].

> *houses that have it, the more the market will take off, just like with mobile phones moving from Nokia phones*" (FG4:2).

Such responses add weight to the notion that consumers are more likely to support the hydrogen transition if it brings increased market choice [320]. In addition, several participants in the industrial towns group stressed the importance of having a warrantee, of at least ten and up to fifteen years, for purchase to be considered a viable option. Furthermore, brand recognition and reputation were explicitly emphasised as critical to market acceptance:

> "*We all want choice, but we also want recognised brands like Worcester Bosch and others that we would be able to trust … To have just one manufacturer … is not going to be the way to go. I think we need to be able to have choices, whether we want one with a long warrantee, different models, things like that*" (FG9:1).

In response, a fellow participant cautioned against the risk of monopoly power and market failure [321,322]:

> "*You've got to have a choice for it to be market competitive, otherwise you end up with a company that has a monopoly … You need those organisations that have experience in manufacturing this sort of equipment because they've already got the supply chain in order … If it's a brand new start-up with everything from scratch, then forget it. If you can afford to, you choose to have a brand name boiler because you only have one of them and there's no back up*" (FG9:2).

A few participants also flagged potential issues that may arise, should the servicing of hydrogen appliances be tied to the manufacturer. One respondent with contacts in the building trade explained how "*they've all got their favourite companies … I know a lot of mates who are plumbers and love Valliant but won't touch Bosch or Reliant*" (FG3:2), while another participant highlighted associated risks:

> "*I suppose the other issue with friends of mine is that certain companies make it difficult for engineers to service their boiler. They want to use their own gas engineers. So, you could get a situation where they are bringing in this new technology and the gas fitters won't be able to service them*" (FG7:1).

Consequently, several respondents stressed the need for a fairer market for repairs and servicing: "*I don't think you want to be tied to a particular service contract. You want to be able to go out to the market and find Joe Bloggs, and not rely on the manufacturer, otherwise they can charge what they like*" (FG7:5). Reflecting the potential for consumer resistance, concern was voiced over the difficulty of securing a reliable repair service, which is "*a struggle already*" and could be exacerbated if hydrogen appliances become "*a niche market*" (FG5:2). These remarks reflect the current risk that qualified hydrogen technicians could be in short supply, at least during the initial phases of the transition [54,215,323].

5.7. Perceived community benefits, risks, and costs

Respondents framed the divers of community acceptance for domestic hydrogen around environmental, health, and economic benefits. The potential environmental and climate change benefits of hydrogen (e.g. for "*cleaning up air pollution*" FG1:2) were mentioned twice as frequently as health benefits. Economic benefits were the least discussed of the three areas and mentioned tentatively in most cases. One participant speculated, "*… employment opportunities also maybe*" (FG3:3), while another commented, "*you would need engineers to install appliances, so I guess people would have to train to do that*" (FG1:3). Representing an optimistic outlook, a respondent from South Wales detailed positive employment prospects for the local community based on recent activities and developments in the region:

> "*Down here, through all my lifetime there has been basically oil and petrol, three of four refineries within two miles of each other. Two of those have closed, but they have reopened as LNG [Liquified Natural Gas] ones. So, it's all new technology … people are now being retrained to do all the new renewable energy jobs … They're highly paid jobs which we needed because our economy was suffering … now the local people are starting to be retrained. My son works in it now … it's positive news for Pembrokeshire*" (FG4:2).

This narrative reflects how citizens may envision prospective hydrogen futures [86] as a source of "hope for the regeneration and maintenance of a community" [324]. Touching on this aspect, one participant was somewhat optimistic about market developments, "*looking at current gas prices, hopefully reduced costs would be a benefit to local communities*" (FG2:6).

Countering this sense of optimism, a community leader stressed the importance of economic risks:

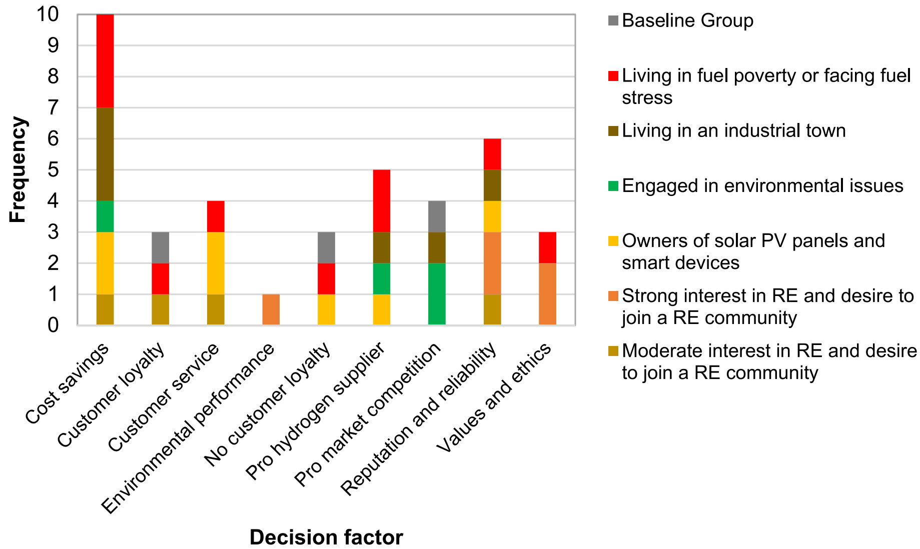

Fig. 12. Factors influencing consumer engagement with energy suppliers.

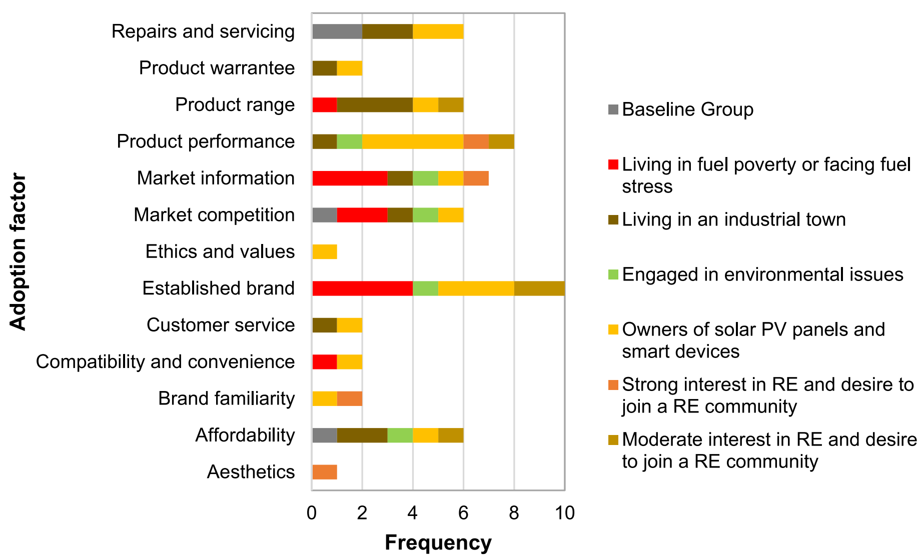

Fig. 13. Factors influencing the potential uptake of hydrogen homes appliances.

"*It's purely based on cost more than anything, so the risks to the community are financial … we live in an area of high social deprivation, so if it cost anybody anymore, then it will just be a no-go*" (FG9:2).

Based on experience working in the retrofit market, a participant from Teesside (Middlesbrough), highlighted the risk of "*potential negativity that could come from a lack of community engagement and buy-in,*" associated with "*the failure of the Green Deal*" (FG8:3) and related policies:

"*When I say the failure, I'm not talking about the finance. I'm talking about the installation and accreditation of those installers and the phoenixing of companies that come and go. It's had particularly detrimental effects on lower- income families around the country. There's been unintended consequences of wall insulation which has actually made properties much worse*" (FG8:3).

Supporting this assessment, studies have documented the inadequacies of the Green Deal [325], which failed to improve insulation standards and building performance [326] following a lack of building regulations [327]. It was suggested that more information should be made available to the public, alongside "*meaningful engagement to get to an understanding of what people want and what they fear, and how they can overcome it*" (FG8:3). As a result, the same participant remained sceptical about the foundations of UK's industrial strategy:

"*I think part of the economic system in this country is we need to see growth in industry, so we'll fund something and create jobs, but the overall impact is more likely to be detrimental than productive*" (FG8:3).

This account highlights the importance of both community acceptance and distributional justice, especially in areas with a history of social deprivation such as Teesside [328,329].

In most cases, other risks to the local community related to changes to local infrastructure and associated disruptive impacts were viewed to be negligible. Participants framed these impacts in terms of increased traffic, noise, and disruption to reliable energy supplies. One respondent (FG2:3) contextualised their answer by citing recent experiences with the changeover to fibre optic internet [330,331], but ultimately viewed the hydrogen switchover as a less disruptive proposition at street level. Instead, risk factors were framed in terms of trust and credibility:

"*The risks are the inconvenience of the roads being dug up and all that stuff. I don't see risks, but I see that it's always outsourced to the cheapest* *bidder, so it has to be done by a company that's reputable and accountable. When they say two weeks, it managed properly and doesn't take four months*" (FG2:3).

On this theme, one participant mentioned the potential for "*geographical upheaval*" in terms of "*digging up roads*," but downplayed these risks off by declaring, "… *let's face it, the road network is already so abominable, a few extra trenches aren't going to make much more of a difference*!" (FG9:2).

Two participants also shared divergent accounts of infrastructural change in Wales, reinforcing the importance of place attachment and local context [332–335]. Notably, one respondent provided a somewhat cautionary tale based on their experience in the north: "*I remember living on an estate where gas came to the area for the first time, but the level of disruption to the road and network, and the amount of traffic and roadworks, that was going on went on for six to nine months*" (FG5:3). By contrast, a retired tradesperson from South Wales trusted in the governance process: "*The infrastructure doesn't worry me in anyway. It's going to be highly regulated and safe. It's always been that way down in Pembrokeshire. I see it will be well-governed with all the laws*" (FG4:2). Another participant shared this viewpoint, explaining how "… *with the regulation and governance, they're not going to take any risks on this, so from a health and safety perspective it should all be covered*" (FG4:1). Such perspectives have been echoed in several studies [162,163,185,186], with evidence suggesting that public trust in regulation reduces concerns over hydrogen safety risks [73].

5.8. Perceptions of spatial dynamics and energy justice

Following information provision regarding the spatial dynamics of the hydrogen transition, participants were asked follow-up questions concerning choice and fairness. The discussion aimed to gauge consumer attitudes towards three key aspects: (1) geographical inclusion or exclusion in the early phases of the domestic hydrogen transition; (2) related equity implications, such as whether consumers should have a choice about adopting hydrogen appliances following a unilateral conversion of their gas network; and (3) whether they would be willing to pay for the costs of the transition if excluded as end-users.

At the outset, several participants asked for clarification about why specific areas and sites are being selected for demonstration projects of trials [336,337], or otherwise considered as potential candidate towns or cities for hydrogen homes [75]. These queries linked to a consensus that more information is needed about alternative low-carbon energy technologies and decarbonisation pathways. Consequently, in some instances, the emerging spatial dynamics of the domestic hydrogen transition – targeted primarily for the industrial north [75] – led to somewhat polarising responses. A minority of respondents, typically from the South of England, expressed concern over the concentration of hydrogen activities around industrial clusters and potential exclusion, with some calling for more action to curb the carbon footprint of London.

Objections of this nature highlight the potential difficulty of satisfying both southern and northern parts of the UK population, at least in the early stages of a potential transition to domestic hydrogen , which is partially reflected by statements in Table 5. Furthermore, references to the environmental benefits of hydrogen remained predominantly urban-centric, although one respondent form Ipswich (FG4:3) also acknowledged the plight of rural areas. Such perspectives illustrate the potential nuance of public perceptions, which may prove counterintuitive to the expectations of policy makers: envisioning hydrogen as a mechanism for regional regeneration to support the UK's post-Covid economic recovery [50,51,338].

Despite a mix of concern and confusion, the advent of hydrogen clusters drew a broadly positive reception based on the premise of industrial reinvigoration [51]. In total, 17 references[34] were made to one of six perspectives (see Fig. 14), with more than half of responses favouring deployment for the industrial north ($N = 9$), contrasted against deployment for London and the Southeast ($N = 4$). Respondents believed the launch of hydrogen homes "*should be selective*" (FG6:2) and "*logical*" (FG9:2), with one participant acknowledging the viability of

Table 5
Consumer perceptions of the spatial dynamics associated with hydrogen homes.

Location	Illustrative statements
Marston Moretaine, East of England (originally from London)	• *They should start with the places that are the worst polluters. Rather than starting off with London who always get everything, start with Humberside and Manchester and places that are industrial* (FG2:3).
Marston Moretaine, East of England	• *By starting in the north, you're then reducing the entire country's footprint by tackling the worst polluters* (FG2:5).
Pembrokeshire, South Wales	• *I don't know if it would be feasible to get all the infrastructure down to us. I can understand it being in a big city, but where I live in a rural area … is it cost feasible to do it?* (FG4:2).
Ipswich, East of England	• *Big cities need something for the emissions … but our countrysides need the help as well* (FG4:3).
Manchester, Northwest England	• *Think about the balance of the population … they talk about bringing the cost down as its rolled out, but if it's not available down in the southeast or other major urban areas, then I can't see how that cost is going to be alleviated for people* (FG5:1).
Chester, Northwest England	• *It makes sense to have those sort of [hydrogen] hubs because the north is known to be a lot more industrial anyway … a great way to make homes and businesses in industrial towns more energy efficient* (FG6:2).
Manchester, Northwest England	• *It's fairer that certain places have it and others don't, and it's also good for leisure places because of the pandemic … to bring more tourism into a particular town … the community could thrive form that and the economy would probably pick up there* (FG6:3).
Falkirk, Central Scotland	• *It makes sense that hydrogen hubs and homes are concentrated in areas of industrial activities, and I suppose the normal criticism is that it's always London and the Southeast that gets all the investment and everything is first there, so maybe this is part of the levelling-up* (FG7:6).
Marston Moretaine, East of England	• *What about down south? It's all up north and I'm only really involved in my local areas* (FG8:6).
Lincolnshire, East Midlands	• *It seems logical to have your storage facilities in industrial estates like they were historically in the 1990s before they were decommissioned* (FG9:2).
Flint, Northeast Wales	• *It should be used in the locations highlighted rather than being launched as a nationwide project because it will be easier to control and maintain in just a few locations at first. I believe it can go through a test run in these locations to determine if it can go nationwide* (FG9:6).
East London	• *London should be on the list and the top priority because of all the carbon emissions and urbanisation* (FG10:2).
Isle of Wight	• *I think it's better to roll it out through the whole of the UK and not only certain regions because there might be those down South that do want to have this. But there's nothing there from the map at the moment, so there should be more fairness there* (FG10:3).

[34] One participant (FG5:5) held a dual perspective on this aspect.

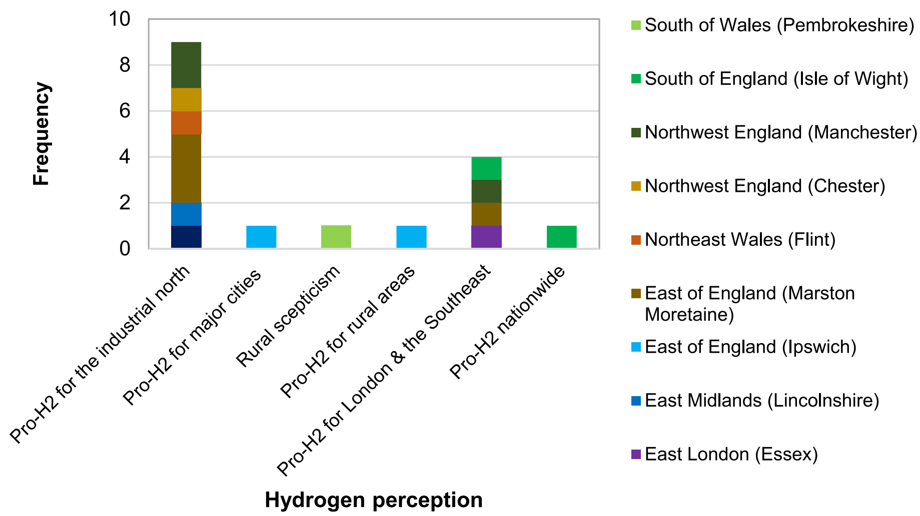

Fig. 14. Consumer perceptions of potential locations for hydrogen homes.

roll-out strategy, despite personal reservations about early adoption:

"*It's a good thing … looking to implement it area- by-area. In due course by 2035, everyone will have changed over to something. I'm just a bit reluctant to be the first one to try it out … And I would want it to be around for a few years before I got involved in it. I wouldn't want to be the first to try it out and then regret that decision*" (FG10:3).

Reluctance and risk aversion towards adopting new technologies is critical factor of social acceptance, with evidence from Ofgem suggesting UK consumers are more accepting of a familiar or established option [159].

Regarding choice dynamics related to the hydrogen switchover, 21 references were made across the sample corresponding to four perspectives, namely, recognising a 'choice deficit' ($N = 2$), being 'choice agnostic' ($N = 3$) or 'pro-choice' ($N = 10$), and finally, arguing that there is 'no room for choice' ($N = 6$). While close to half of the comments were in favour of choice (see Fig. 15), some respondents were adamant that the switchover should be mandated due to the pressing need to decarbonise [339,340] and the nature of large-scale energy transitions [311,341,342]: "*Did they have a choice when town gas was switched off? No, you've got to do it. It's an entire municipal engineering project. There's no room for choice, it just needs to happen" (FG9:2).*

Speaking from direct experience, another participant mirrored this perspective, "*… we went from coal gas to natural gas. Would it make any difference if we moved to hydrogen? There was no choice at the time and there no charge"* (FG1:4). However, this viewpoint sometimes came into conflict, as reflected in the following perspective:

"*I'm in two minds about it. I feel like we should not have a choice because we need to make this change. But on the other hand, the price is going to affect us as individuals, so we do need that choice*" (FG10:4).

Representing the pro-choice camp, one respondent argued in favour of deeper levels of consumer engagement to support social acceptance, while cautioning against the risk of exacerbating the North-South divide [343,344] by compromising the levelling-up agenda [338,345]:

"*If everyone has a choice though, the more people that can buy into it psychologically and emotionally … giving the personal choice is important. I think everyone should have it free or equally, otherwise you have the same issue with the North-South divide. It's all about levelling up and you can't do that if some places don't enjoy the benefit*" (FG2:3).

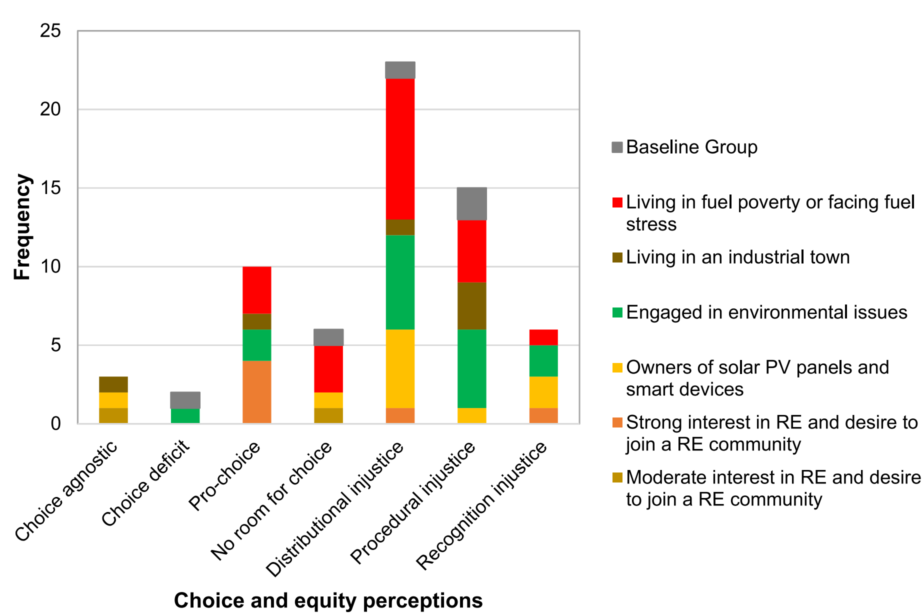

Fig. 15. Consumer perceptions of choice and equity implications.

In many cases, comments on choice dynamics flowed into detailed discussion about equity implications, with the themes of distributional (N = 23), procedural (N = 15), and recognition injustice (N = 6) emerging within most focus groups. As depicted in Fig. 15, references to distributional injustice were twice as frequent as other energy justice aspects, with several insights offered:

> "*You don't want cheaper energy for one part of the country for a long time and other people getting left behind. Maybe you could share out the wealth somehow. If one area is getting cheaper, you could still pass on the savings to other parts of the country*" (FG3:3).

Another respondent highlighted the risk of public resistance and potential backlash:

> "*You can imagine the uproar if they announce that it's only being offered to certain parts of the country due to the exclusion. If they are trying to convince people that it's a good thing … then everyone will want to be included, which doesn't sound like it's possible*" (FG7:6).

Framing things from a similar standpoint, one participant worried about higher costs for early adopters and the risk associated with "*penalising a certain area who are moving over first*" (FG9:1). Moreover, the following critical perspective was supported across parts of the sample:

> "*If there's no chance whatsoever that we are going to benefit from it, why should we pay for it? If the long-term plan is that most of Britain is going to have it, then great, pay for it now through our taxes. But if there are lots of areas that are never going to get it, why should they pay for it then?*" (FG4:2).

Specifically, consumers facing fuel poverty pressures expressed the highest level of concern over distributional injustice (N = 9; 39.1 %) and energy injustice in general (N = 14, 31.8 %), followed by citizens engaged in environmental issues (N = 13, 29.5 %)., who also expressed most concerns over procedural injustice (N = 5; 33.3 %). This result suggests alignment between parts of the population most concerned about energy injustice and climate injustice, respectively. Given the frequency and intensity of comments on this theme (see Supplementary Note 8), it is evident that community acceptance could hinge on how choice architectures [346,347] influence the emerging spatial dynamics, logistics, and equity implications of the transition.

5.9. Perceptions of individual risks and energy vulnerabilities

Following the discussion on community wide impacts and potential disruptions at street level, participants considered their tolerance level for being temporarily disconnected from the gas grid during the hydrogen switchover (see Supplementary Note 9). Fig. 16 shows that the highest frequency of responses included 1–2 days (N = 4), 2 days (N = 4), and 2–3 days disconnection (N = 5), while less than 1 day (N = 2) and up to 1 week (N = 1) emerged as notable outliers among responses (N = 23).[35] Additionally, one respondent offered a unique perspective which circumvented a direct answer and reflected grievances with their current gas connection, "*I'm willing to be disconnected for how long I need to for the purpose of the improvement of the service*" (FG9:8).

Speaking from direct experience, one participant explained the contingencies involved with short-term disruption:

> "*The disconnection aspect depends on the month of the year. I went three days with a gas boiler last January and that's plenty. I wouldn't want to repeat that, and I have a* log *burner so it could have been worse. At least we had one room that was warm in the house*" (FG1:1).

Acknowledging that tolerance thresholds would depend on the season, respondents agreed that the switchover must be scheduled for the summertime, as it not only "*makes the most rational sense*" (FG10:4), but may help circumvent negative impacts: "*… during the summer, you would feel it less and that's important and a lot better for vulnerable and elderly people and those with disabilities … you need to consider everyone here*" (FG10:3).

Supporting research findings [72,78,163,185], several participants expressed additional concerns over impacts on vulnerable individuals and households during the hydrogen switchover. One respondent underlined how "*you have to take into account people with health problems*," while another explained that their mother "*has the heating on every single day of the year, so you've got to look at people that are old and vulnerable as well*" (FG9:1). Consequently, tolerance levels were tied to personal circumstances such as household demographics and ability to cope with the disruption.

Reflecting on their recent experience of showering at the gym for "*about four days in summer*" due to a gas leak, one participant shared their view in detail:

> "*The disconnection period depends on people's circumstances. If you've got a family with young children … but you might have someone who can go stay somewhere else for the week … but it's an individual thing really. Some people can deal better with it, but others like the elderly, handicapped or people with children won't be able to*" (FG7:1).

Respondents further suggested how showers could be taken at other places, such as the local swimming pool (FG5:4), or a nearby hotel, if necessary (FG9:1), or preferably at a friend's house (FG3:3).

In addition to scheduling for the summer months and accounting for energy vulnerabilities, participants relayed the need for information provision, communication, and planning to help minimise the length and extent of the disruption, which should be delivered responsibly by involved parties: "*… so if they say for example that you're going to be off for three days, then it would have to take that, not you're going to be disconnected for another week … that would be the crunch really*" (FG1:3). Consequently, some specific mitigating measures were proposed to help manage the disruptive impacts of the switchover, as discussed in Table 6. Additionally, some respondents elaborated on their willingness to tolerate home visits from engineers and technicians during the switchover, which implied disruption for up to a few days would be tolerable in most situations, as evidenced within Table 7.

5.10. Inferences from multigroup analysis

To complete this part of the analysis and consolidate the empirical contribution, five metrics are compared at the sub-group level to derive comparative insights on social acceptance. Fig. 17 integrates two measures of public trust in the government (low and partial), two measures of market acceptance (higher costs and cost parity for appliance purchase), and a combined measured of energy justice (distributional, procedural, and recognition) to assess at-risk dimensions in relation to consumer segments. Cost parity, and to a lesser degree partial trust, are included to account for more neutral perspectives which could potentially undermine social acceptance, alongside overtly negative factors. Additionally, the inclusion of these two metrics increases the total number of measured factors by over 20 % (N = 61 to N = 74).

The following patterns are detected which should be comprehensively evaluated in subsequent large-sample studies including cross-country analyses. Respondents living in fuel poverty or facing high levels of fuel stress, together with participants living in an industrial town, present the highest mean score across the five metrics (M = 1.8), followed by citizens engaged with environmental issues (M = 1.4), and those with strong interest in RE energy and joining a RE community (M = 1.2). Consistent with the notion of a control group, the baseline group ranks below these segments (M = 1.0), but above owners of solar PV and smart home technologies (M = 0.8), as well as consumers with moderate interest in RE and joining a RE community (M = 0.4). While these

[35] This metric was evaluated at the sample level as tolerance levels are considered to be more associated with socio-demographic variables as opposed to various consumer segments.

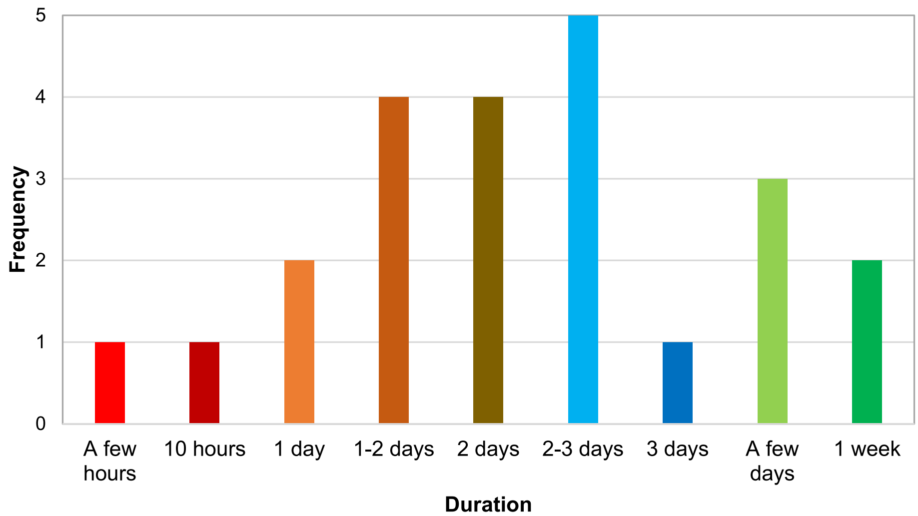

Fig. 16. Tolerance limits for temporary disconnection form the gas grid.

Table 6
Proposed mitigation measures for minimising disruptive impacts and risks.

Participant	Illustrative statements
FG1:5	• *Sufficient warning to either go stay with somebody or to make other arrangements … as long as it was only for a few days maximum because it would indeed be very disruptive to your day-to-day life*
FG4:1	• *I think communication is key. If you can plan for these things … and prepare for it … but I think when it's just landed on you short notice, then it's more challenging. So, I think the positioning and communication would be key for this*
FG5:5	• *They should better inform people about how they can get by without the gas boiler or cooker for a few days during the switchover, with guides about how to get by, so they can see the best way to manage without gas for say two days*
FG9:1	• *I think they do put people who are vulnerable on a certain register, so they are better taken care of during disruptions, but, yes, we need more reassurance about this*
FG9:2	• *Those things [i.e. disruption or burden to energy vulnerable households and others] could be mitigated by surveying different households to see how it would impact them*

Table 7
Attitudes towards engineers and technicians visiting the home.

Participant	Illustrative statements
FG3:1	• *It's no problem for gas engineers and technicians to enter the home, as far as I'm concerned.*
FG3:3	• *It depends on how long they are in the home for, before it becomes a bit intrusive.*
FG4:1	• *I think if they say they're going to need to come in between three to five times, but if it's ten times, it's going to get excessive. So, I think it's all about positioning and having the workers trained so they minimise mess … I think it would be tolerable.*
FG4:2	• *I'm willing to tolerate visits from engineers and technicians until the job is done, as long as its not messy and they tidy afterwards. They've all got jobs to do, and we've all got to make a living. So yeah, I'd be tolerant and … quite happy to put up with a bit of mess and nose to make it more sustainable for the future.*
FG6:1	• *As long as the engineers aren't coming for days and days. You don't mind some disruption if it's the odd day. Will they be digging up the roads?*

findings can be considered exploratory due to the limited sample size, the results reflect the prevalence of fuel poverty in northern regions of the UK, which speaks to the issue of the North-South divide. Consequently, the most at-risk segments for accepting the transition to hydrogen homes may correspond to consumers who are untrustworthy, price pessimistic, and despondent about prospects for energy justice.

6. Critical insights on acceptance dynamics

6.1. Trust deficit recovery

This analysis highlights the extent to which socio-political acceptance is currently hampered by a trust deficit in the government and further stifled by a lack of confidence in energy suppliers, which for some parts of society equates to pervasive criticism and underlying scepticism. At present, trust in these actors remains weak, if not eroded, across many parts of society, following the COVID-19 pandemic and due to the current cost-of-living crisis [348]. Several focus group respondents attested to this reality, while some held out more optimism for positive change, or were otherwise more insulated from socio-economic shocks. More encouragingly, trust in stakeholders such as Ofgem, trade bodies, non-governmental organisations, and research institutes appeared comparatively higher. While divergent perspectives may prevail due to socio-economic and socio-psychological factors, there is a mounting need to address undesirable trust and power dynamics, which continue to subvert the energy transition agenda and potential for a 'just hydrogen economy' [349].

In turn, socio-political acceptance is highly sensitive to the actions of the government and energy companies, which may be dictated by foreign affairs. For example, it remains to be seen how the ongoing Russia-Ukraine conflict [31,32] will impact socio-economic conditions and political stability within the UK. Additionally, unpredictable exogenous shocks such as extreme weather events [350–352] [36] can significantly impact socio-political acceptance over the short-term, contingent upon the reactions of government, industry, business, and media representatives.

Implementing 'hydrogen justice' [353] will require mitigating "the dangers of energy politics" [354], through long-term commitment and observable action towards overturning a legacy of failed energy policies [326,355]. Citizens seek fairness from both the public and private sector when it comes to enacting heat decarbonisation and related net-zero measures, which calls for tangible action across the two main pillars of energy justice [241]. Foremost, principles of fairness and equity – aligned to enacting procedural and distributional justice – should be upheld to foster recognition and restorative justice [239,356,357], especially across industrial heartlands of the UK [114].

In response, corruptive practices, including the subversive aspects of

[36] Notably, two of the focus groups coincided with Storm Eunice (February 14–19, 2022) [351].

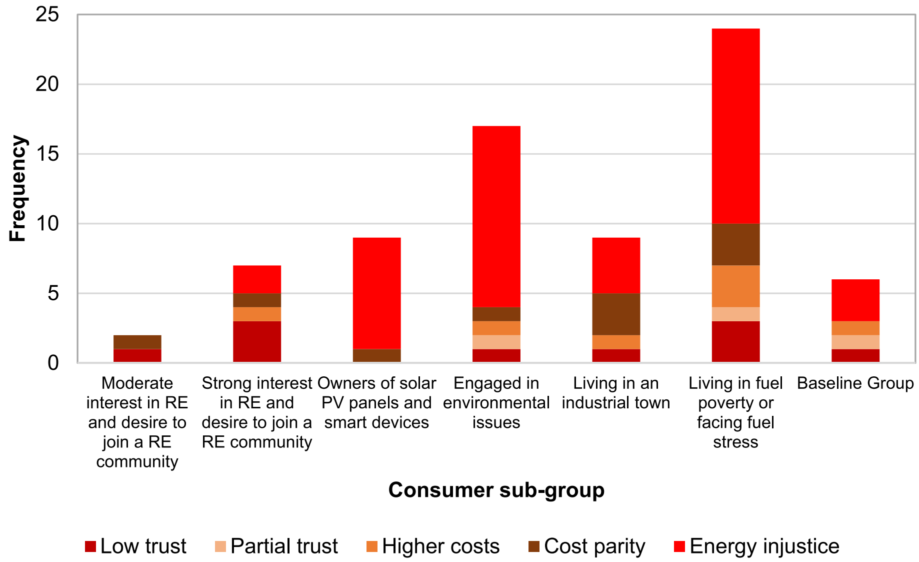

Fig. 17. Potential social resistance to hydrogen homes across consumer sub-groups.

lobbying, should be rooted out in favour of empowering independent statutory bodies, such Ofgem and the Committee on Climate Change (CCC), and prioritising public consultation processes aligned to transparency and inclusiveness (i.e. procedural justice). In tandem, policy makers and stakeholders should support the equitable distribution of costs, benefits, and risks when it comes to enacting the hydrogen switchover and wider decarbonisation agenda, which calls for decisive action on reforming the energy sector (i.e. distributional justice). While the notion of 'deficit recovery' is typically applied to discussions of a financial nature [358], the proliferation of global trust deficits across multiple economic sectors [359–361] marks the urgency for a strategic plan to rebuild a foundational level of public trust in the government and energy industry.

6.2. Price pledges, market competition and consumer choice

Willingness to pay for hydrogen appliances, and by proxy market acceptance, depends on the interplay between purchasing and running costs. However, the former would likely present more of an immediate barrier to consumer uptake, should boiler manufacturers fail to deliver on their current price promise [105]. At present, hydrogen boilers are anticipated to cost less than heat pumps, at least during the initial stages of the transition. While gas-heating may prove a less capital-intensive investment compared to heat pumps, it is apparent that most consumers would resist any price hike, even if hydrogen succeeded in delivering green energy. As a result, there was an underlying consensus that financial security is a stronger motivational driver than perceived environmental benefits.

Given that respondents were not briefed about the recent price promise of boiler manufacturers [105], attitudes towards potential hydrogen adoption proved somewhat positive. There was expectation that hydrogen appliances would not cost much more than current gas appliances, at least for boilers specifically. Should the price promise be delivered, there could be limited grounds for consumer resistance towards investing in a hydrogen boiler; provided there is no obligation to replace a relatively new or well-functioning boiler prematurely, and so long as alternatives such as heat pumps remain somewhat less price competitive.

For owners of relatively new appliances, as well as consumers facing economic hardship, motivating a switch to hydrogen homes would call for a tangible financial incentive, in addition to securing the current price promise. Consequently, the risk of further increases to energy bills is a significant barrier to deploying hydrogen homes, which could undermine the wider 'Gas Goes Green' campaign [362,363]. However, respondents had a lower expectancy that energy bills would increase further if hydrogen were to replace natural gas, whereas appliance purchase was not expected to be cheaper for the most part. Over both the short- and long-term, consumers would need strong assurance that domestic hydrogen adoption would not incur economic losses or impose undue financial risks.

Should cost factors align to expectations, market acceptance will still rest on other aspects of energy markets, namely, the role of suppliers, manufacturers, and retailers. Consumers are wary of the business models and profit motives that drive adverse and irresponsible decision-making; calling for a competitive market environment where both incumbents and new hydrogen-specific suppliers would compete for modest market shares. While the state of the energy market has left consumers with little sense of loyalty, evidence suggests that repeat subscription is plausible so long as reputation, reliability, quality, and customer service remain intact [164,204]. However, consumers are quickly inclined to seek a better deal when one of these characteristics begins to falter.

Mirroring perspectives on energy suppliers, consumers caution against the negative impacts of monopolistic or oligopolistic markets, citing the need for competition and product diversity. Choice is seen as a driver of better product quality and more reliable supply chains, which can help protect customers from limited market access to maintenance and repair services. Compared to energy suppliers, brand name, recognition, and reputation have a stronger influence on decision-making, however, consumers likewise value affordability and reliability, as well as security in the form of a long-term warrantee.

Overall, consumers appear somewhat open to the idea of switching to hydrogen; provided there is a future 'price pledge' of some description on energy bills, which would help support more transparent decision-making on appliance purchase. Although general attitudes towards a prospective market for hydrogen appliances appear mostly positive, this acceptance dimension remains constrained by high levels of dissatisfaction with energy suppliers regarding factors such as cost, reliability, and customer service, which deepen existing trust deficits.

6.3. Hydrogen legitimacy and levelling-up

Community acceptance will hinge on how environmental, social, and economic benefits are communicated and delivered, both to hydrogen and non-hydrogen users. Broadly, there is a sense of support for deploying hydrogen homes across industrial areas as part of the levelling-up agenda. While respondents may be somewhat unfamiliar with the concept of reinhabiting fossil fuel sites [237], this approach may gain public approval in line with the premise of industrial reinvigoration. Reflecting economic opportunities outlined in the UK Hydrogen Strategy [29], industrial regeneration is more likely to gain public support when retraining and upskilling are delivered to support high-quality jobs for local communities. However, even when economic benefits are anticipated, community engagement and information campaigns remain critical to securing local acceptance.

This study suggests parts of the population may also question the legitimacy of the UK's industrial strategy as a driver of socio-economic benefits. To counteract social resistance, policy makers will need to clearly communicate and justify the emerging spatial dynamics of the prospective transition to hydrogen homes. At present, London and the Southeast, as well as rural areas, are less prioritised in the current heat decarbonisation agenda, at least in respect to hydrogen, which may trigger social resistance due to perceptions of exclusionary policy making.

In view of spatial dynamics and equity implications, government and key stakeholders should aim to leverage prospects for socially acceptable decarbonisation pathways through two key pillars: (1) increasing the social acceptability of hydrogen homes in locations where techno-economic feasibility can be established; and (2) communicating low-carbon alternatives such as heat pumps and district heat networks for locations where hydrogen proves less suitable or unfeasible, in line with the Heat and Buildings Strategy [101]. In terms of the first pillar, the logistical barriers of the switchover were recognised within this study, as demonstrated when discussing choice dynamics, "*I understand people's preference for choice, but a lot of the population wouldn't switch without a nudge, and the infrastructure needs to be there before a choice can even be offered*" (FG8:7). Without delivering on the second pillar, as also reflected by several comments within this study, deploying domestic hydrogen may otherwise risk perverse impacts in terms of aligning with the levelling-up and 'leave no one behind' agendas [364,365].

6.4. Safeguarding against energy vulnerabilities and minimising disruption

Based on a review of the available literature Gordon et al. [73] concluded that the disruptive impacts of the switchover rank as a 'major' barrier to domestic hydrogen acceptance at both the community and household level. However, this study emphasises that disruptive impacts at the community-level are viewed to be less of a concern than the short-term impacts to households, following temporary disconnection from the gas grid. From an overall health and safety perspective, respondents appear relatively confident that adequate regulatory and governance measures will be taken during the switchover period to safeguard against unnecessary disruptions at street level and undue risks.

There is a consensus that disconnection should be capped at a maximum of three days and preferably kept to less than two days. By contrast, tolerance limits appear somewhat higher and more flexible when considering visits to the home from gas engineers and technicians. This divergence reflects the clear distinction between short-term disconnection from the gas grid compared to intermittent disruptions of a human nature. The first scenario may exacerbate energy vulnerabilities and cause direct harm, even if the switchover is carried out during the summer months, while the second situation is primarily associated with minor inconvenience. Respondents appear highly cognisant of this reality, stressing the need to ensure adequate provisions for vulnerable households to minimise negative social and health impacts. Furthermore, the results highlight the potential benefits of consumer engagement on this specific topic, since focus group participants demonstrated a pro-active attitude towards mitigating the impacts of temporary disconnection.

7. Conclusions

This study makes a timely contribution to the discourse on social acceptance for emerging energy technologies, contextualised to the case of domestic hydrogen in the UK. Although this analysis focuses on a specific country case, the findings have international relevance to other nations seeking to transition to green gas for home heating, and possibly cooking, such as the Netherlands, Germany, and Australia. Reflecting the largely global trust deficit in governmental institutions and the energy sector, comments from UK focus group participants are partly generalisable to other populations, such as European neighbours facing energy insecurity following the Russia-Ukraine conflict. Furthermore, through an integrated, mixed-methods multigroup analysis, this research provides a more nuanced understanding of consumer preferences, which may be analysed in subsequent international studies to elucidate cross-cultural findings on energy acceptance.

This analysis provides insights into aspects of socio-political, market, community, and household acceptance related to hydrogen homes, as gauged from the perspective of different consumer groups. The findings reinforce that socio-political and market acceptance are strongly interlinked dimensions of domestic hydrogen acceptance [75]. Principally, persistent consumer dissatisfaction with energy suppliers has eroded the foundations of trust in government and the energy industry for much of society. The profiteering of energy companies against often vulnerable consumers presents a major challenge to changing the status quo, which is aided little by elements of deep mistrust in the central government. Consequently, measures to reform energy markets may prove invaluable to reversing the trend of dissatisfaction with suppliers and establishing the conditions for deploying hydrogen homes in the future.

Synthesising the findings, socio-political acceptance appears the most at-risk dimension, whereas community acceptance is comparatively stronger; following general support for the deployment of hydrogen homes around industrial clusters, which may act as a socio-economic stimulus for local communities. At the community level, consumers perceive hydrogen to offer a somewhat positive vision for the future, while the prospect of linking residential heat decarbonisation to industrial strategy is generally accepted. Evidence also suggests that disruptive impacts are perceived to be tolerable at the community-level and moreover, at the household-level. However, significant uncertainties remain over implementing distributional justice, which entails important implications for deploying hydrogen homes, as reflected by recent events in Whitby village and ongoing developments in Redcar (Northeast England).

There is significant scope to build nationwide acceptance for the low-carbon transition by better communicating the role of green gases and electrification in a net-zero future, so that households can engage more meaningfully as active decision-makers with informed views. Consequently, there are clear opportunities for local actors and stakeholders to engage with driving the residential energy transition as knowledge brokers, which would likely yield a positive multiplier effect on community acceptance and trust. Furthermore, it is evident that consumers will require the hydrogen actor-network to enact commitments towards delivering choice, fairness, and equity. This responsibility includes fulfilling, if not bettering, the current price promise while also endorsing a price pledge on energy costs. In parallel, social acceptance will hinge on how consumers perceive hydrogen's alignment towards alleviating energy poverty and improving the environment.

By extending the evidence base, this study offers strategic insights to support more reflexive decision-making on the role of hydrogen in the energy transition. By analysing patterns in qualitative data, the research identifies causal mechanisms behind social resistance, which should be mitigated to facilitate domestic hydrogen acceptance. Stakeholders can internalise findings from this analysis to leverage potential synergies between social acceptance dimensions, for example by strengthening public trust to improve perceptions of energy justice and corresponding support for hydrogen at the community-level. Additionally, the results highlight the need to account for consumer heterogeneity in residential decarbonisation pathways, which can be realised by integrating place-specific policies and segment-specific strategies.

This study is the first to operationalise qualitative data from online focus groups into a comprehensive mixed-methods analysis on hydrogen, which integrates both a quantitative and comparative focus. However, until validated by subsequent large-sample survey studies grounded in rigorous statistical analyses, the descriptive results of this small-sample study should be considered as exploratory inferences. Despite some limitations, the richness of qualitative evidence and patterns identified within the quantified data consolidate the importance of several acceptance factors and underscore the relevance of consumer heterogeneity. Ultimately, realising visions for domestic hydrogen futures calls for both techno-economic feasibility and social acceptability, wherein public trust in the government, consumer confidence in energy markets, and community-wide belief in the potential for energy justice are critical components of a prospective transition to hydrogen homes.

CRediT authorship contribution statement

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

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.

Data availability

Data will be accessible publicly on our institutional data repository.

Acknowledgments

This research was supported by the UK Research and Innovation Engineering and Physical Sciences Research Council (EPSRC) Grant EP/T518104/1, and sponsored by Cadent Gas Ltd.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113810.

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