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Original research article

Divergent consumer preferences and visions for cooking and heating technologies in the United Kingdom: Make our homes clean, safe, warm and smart!

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ABSTRACT

Decarbonising the global housing stock is imperative for reaching climate change targets. In the United Kingdom, hydrogen is currently being tested as a replacement fuel for natural gas, which could be used to supply low-carbon energy to parts of the country. Transitioning the residential sector towards a net-zero future will call for an inclusive understanding of consumer preferences for emerging technologies. In response, this paper explores consumer attitudes towards domestic cooking and heating technologies, and energy appliances of the future, which could include a role for hydrogen hobs and boilers in UK homes. To access qualitative evidence on this topic, we conducted ten online focus groups ($N = 58$) with members of the UK public between February and April 2022. The study finds that existing gas users wish to preserve the best features of gas cooking, such as speed, responsiveness and controllability, but also desire the potential safety and aesthetic benefits of electric systems, principally induction hobs. Meanwhile, future heating systems should ensure thermal comfort, ease of use, energy efficiency and smart performance, while providing space savings and noise reduction, alongside demonstrable green benefits. Mixed-methods multigroup analysis suggests divergence between support levels for hydrogen homes, which implies a degree of consumer heterogeneity. Foremost, we find that domestic hydrogen acceptance is positively associated with interest and engagement with renewable energy and fuel poverty pressures. We conclude that internalising the perspectives of consumers is critical to enabling constructive socio-technical imaginaries for low-carbon domestic energy futures.

1. Introduction

Following several decades of mixed scientific, technological, and commercial progress [1,2,3,4], hydrogen is increasingly recognised as an important pillar of the energy transition [5,6,7]. Given its versatility as a decarbonised gas and chemical store of energy, hydrogen offers an important energy vector for supporting global decarbonisation [8,9,10] across key sectors of the global economy [7] including industry, power, transport and buildings [11]. Hydrogen continues to attract increased attention from policy makers as a means for reducing carbon emissions [12,13,14] and strengthening national energy security [7,8,15]. This perspective is well-reflected in the British Energy Security Strategy [16][1] among other national hydrogen strategies [17,18,19,20,21]. In countries with large-scale natural gas infrastructure such as the UK, hydrogen may also present an opportunity for supporting residential decarbonisation [11,22], foremost, in proximity to the country's largest industrial clusters [23,24,25,26].

Converting the UK gas network to transport hydrogen has been

Abbreviations: CCUS, Carbon Capture, Utilisation and Storage; EPSRC, Engineering and Physical Sciences Research Council; GDNOs, Gas Distribution Network Operators; Ofgem, Office of Gas and Electricity markets; RE, Renewable energy; UKERC, UK Energy Research Centre; UK-SHEC, UK Sustainable Hydrogen Energy Consortium.

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[1] The British Energy Security Strategy recently doubled the low-carbon hydrogen production target to 10GW by 2030, adding further momentum to the emerging hydrogen economy [16].

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discussed in the literature since the early 2010s [27,28,29], following two key projects funded by the Engineering and Physical Sciences Research Council (EPSRC) [30,31].[2] Subsequently, hydrogen became increasingly discussed in UK energy policy during the mid-to-late 2010s [32,33,34].[3] Employing the UK TIMES model, Li et al. [35] concluded that low-carbon hydrogen is likely critical to greenhouse gas emissions reduction in residential heating, which has been echoed by other research findings [22,36,37]. Accordingly, some scientists posit that "hydrogen has a potentially important future role as a replacement for natural gas in the domestic sector in a zero-carbon economy for heating homes and cooking" [36:30190]. Nevertheless, the global warming potential of hydrogen [38,39] and associated environmental impacts such as methane leakage rates [40] and nitrogen oxides emissions [41,42] need to be examined further when considering future transition pathways [43,44,34,45].

Growing ambition and commitment towards realising a national hydrogen economy culminated in the release of the UK Hydrogen Strategy in August 2021 [11], following the government's Ten Point Plan for a Green Industrial Revolution [46]. The strategy aims to gather a robust evidence base by 2025 through a series of local trials and demonstration projects, ahead of strategic decision-making on the role of hydrogen for homes in 2026 [11,44].[4] Supporting the low-carbon transition, current policy plans will see gas and oil boilers banned from newbuild homes by 2025 to meet zero-carbon regulations [47], underscoring the trajectory of heating technologies in the UK.

There are around 21.2 million gas appliances and 12.7 million gas cookers (hobs and ovens) installed across the UK housing stock [48,49]. Gas is used for space heating in approximately 84 % of households [48] and remains the dominant fuel for cooking on a hob, whereas electricity is significantly more prevalent than gas when it comes to ovens [50]. While heat decarbonisation remains a significant challenge for achieving net zero [51], the emissions from cooking are embedded in the networks, institutions, and infrastructure of the wider energy system [52]. As noted by Hargreaves et al. [53], cooking practices cut across multiple regimes and system boundaries including energy, food, water and transport, thereby presenting an array of 'trigger points' for decarbonisation [52].[5]

To date, there is a clear dichotomy in the literature, as underscored by a recent output from the UK Energy Research Centre (UKERC) which examined the social side of switching from natural gas cookers and hobs to low-carbon alternatives [52]. Due to an information deficit, Khalid and Foulds [52] relied exclusively on the broader literature engaging with "heat decarbonisation, technology transition, carbon and energy reduction, home retrofitting and sustainable food consumption" to frame the study.[6] The existing knowledge gap is especially noteworthy given recent market trends, which has seen the popularity of induction hobs and corresponding sales increase within recent years [52].

Although converting to a hydrogen home, as currently envisioned, would entail a switch to new heating and cooking appliances, there is likewise scarce evidence regarding consumer perspectives of adopting hydrogen cooking appliances [54,55,56,57]. Almost exclusively, the focal point remains hydrogen heating, whereas hydrogen cooking is typically overlooked or of secondary interest. An extreme case is the UK Hydrogen Strategy which has over 400 mentions of 'heat' or 'heating' while 'cookers' or 'cooking' are referred to just five times [11]. Similarly, in their study on the public acceptability of hydrogen homes, Williams et al. [58] referred to heating approximately 16 times more than cooking. The study reported a single noteworthy finding regarding domestic heating technologies:

> …participants also disliked the idea of cooking on electric cookers, with a preference for gas cookers. In some cases, induction cookers were felt to also meet cooking needs, however, many had not necessarily experienced cooking on this type of cooker and remained sceptical [58:29].

Following these observations, this study attributes equal interest to consumer preferences for cooking and heating technologies in the UK context. Firstly, we address the research gap identified by Khalid and Foulds [52] by examining consumer preferences for existing cooking and heating technologies. Building on this contribution, the rest of the analysis aims to advance social science research on consumer attitudes towards hydrogen homes [59,60,61,62], while responding to the call for primary research on the social implications of transitioning to low-carbon cooking technologies in the developed world [52]. Critically, this study departs from previous approaches [56,59,60] by employing online focus groups as the primary method of data collection, as opposed to online or paper-based surveys. Adopting this approach, the paper makes an empirical and methodological contribution to the hydrogen futures literature [12,63,64].

The study has four distinct aims which are reflected in its structuring. Firstly, we investigate how users perceive the main advantages and disadvantages of current domestic cooking and heating technologies. Secondly, we evaluate consumer willingness to adopt hydrogen appliances and examine how this translates into wider support for living in a hydrogen home. Thirdly, we explore how attitudes towards domestic hydrogen may differ among specific consumer segments. Lastly, we assess how consumers perceive domestic cooking and heating technologies of the future. In its totality, this exploratory study can help guide future research on this topic, while offering insights to stakeholders regarding the role of consumers in the domestic hydrogen transition.

Following this introduction, Section 2 reviews the literature on consumer preferences for domestic energy technologies and hydrogen home appliances. Next, Section 3 describes the materials and methods. Section 4 reports the results on consumer attitudes towards domestic cooking and heating appliances, while Section 5 explores consumer perceptions of hydrogen homes. Section 6 synthesises this evidence base by evaluating consumer preferences for future cooking and heating technologies, which includes a multigroup analysis of domestic hydrogen acceptance. The discussion and conclusions are presented in Section 7, which maps a future research agenda and notes the limitations of the study.

2. Literature review

Given the lack of data on low-carbon cooking and consumer acceptance [52], Section 2.1 reviews consumer preferences for low-carbon heating technologies as a means for understanding wider domestic energy attitudes and behaviours, and by proxy cooking practices and preferences. Next, Section 2.2 reviews the literature on domestic hydrogen acceptance, while Section 2.3 focuses on the duality of residential decarbonisation vis-à-vis the notion of a hydrogen home. Section 2.4 documents key information regarding fuel poverty pressures and energy vulnerabilities facing UK households, reflecting our inclusion of fuel poor participants. Lastly, Section 2.5 highlights the interplay

[2] The UK Sustainable Hydrogen Energy Consortium (UK-SHEC) and the Hydrogen and Fuel Cells Supergen Hub.

[3] For example, in 2018, the Committee on Climate Change released its "Hydrogen in a low-carbon economy" report, which supported a role for hydrogen in residential decarbonisation as part of a hybrid heating system [34].

[4] Notably, Redcar in North Yorkshire and Ellesmere Port, Cheshire, have been shortlisted to host the UK's first hydrogen village trial for 2000 homes [218,219], wherein households will switch to hydrogen-fuelled appliances for heating and cooking [60,220].

[5] Cooking accounts for around 2 % of total UK carbon emissions, compared to around 14 % for domestic heating, most of which is attributed to gas boilers [52]. However, the emissions from cooking are embedded in the networks, institutions and infrastructure of the wider energy system.

[6] The deficiency of studies on consumer preferences for cooking technologies in western economies [221] also stands in stark contrast to volumes of literature tackling consumer engagement with improved cookstove programs in the developing world [222,223,224,225].

between the literature on socio-technical imaginaries and hydrogen futures.

2.1. Consumer preferences for low-carbon heating technologies

Regarding heat decarbonisation, social science research indicates how the dynamics of domestic heating practices are highly variable [65,66], with behaviours and practices shaped by a wide range of factors.[7] It has been theorised that divergent heating behaviours can be analysed by seeing where consumers fall within the following scales: spending versus comfort; single space versus differential space; regular versus irregular routines; unpredictable versus predictable routines; and self versus others [67]. Contingent on the mix of technology pathways, achieving deep decarbonisation across the residential sector may call for significant changes to consumer behaviour [32].

Reviewing the empirical literature, Kastner et al. [68] highlighted that consumers base their household energy investments around perceived consequences for energy security, thermal and operational comfort, finances and the environment. Regarding finances, Chapman et al. [69] found that 45 % UK respondents considered upfront cost to be more important than running cost, while 50 % considered the upfront costs associated with the installation of energy efficiency measures would be too expensive ($N = 5022$). Based on a comparative assessment of "the demographics and geography of household heat decarbonisation in Europe," Sovacool et al. [70:1] also found that consumers attribute more value to systems that bring economic, environmental, and cultural. Other important factors include health, safety, convenience, and comfort [70:1]. Notably, 83 % of UK respondents ($N = 2000$) valued personal control of their heating system[8] and 79 % believed low-carbon heating should be reliable and easy to use, while 56 % considered heating to be the most important domestic energy service [70]. Other studies echo these findings, with Andersen et al. [71] noting the importance of autonomy, economy and comfort in the context of district heating in Denmark, while Hagejärd et al. [72] highlight the importance of thermal comfort and control for consumer acceptance of residential space heating in Sweden.

Spatial constraints, disruptive impacts [73], noise and appearance [58] account for other important considerations when considering domestic heating appliances. For example, comparing hydrogen and heat pumps, Williams et al. [58:30] noted that "the greater use of space, lack of responsiveness, additional noise generated by the pump, and the overall look…did not tie in with perceptions of a smart home" [74,75,76]. Existing heating technology may also prove a significant determinant of subsequent technology choice [77]. Incorporating heterogenous households' preferences into the UK times model, Li et al. [35] found that 76 % of 1–3-bedroom households and 78 % of 4-bedroom households with gas heaters would opt for the same technology again.

In addition to existing technology and dwelling type (including number of rooms), age, location and awareness of eco-technology may influence homeowners' preferences for heating technologies [35]. Willis et al. [78] found that age was a significant factor in the adoption of micro-generation technologies such as solar thermal, solar photovoltaic and wind power in the UK, with consumers over 65 years old proving less willing to adopt these technologies than younger demographics. Arguably, the adoption of low-carbon energy technologies for the UK residential sector may be hindered by the country's aging population [78].

Overall, the literature suggests that low-carbon heating systems should be user-friendly and compatible with other devices, provide controllability and reliability, guarantee privacy and protect personal data, and come from credible manufacturers, preferably with performance guarantees and a customised user manual included [70].

2.2. Domestic hydrogen acceptance

Domestic hydrogen acceptance remains a nascent research area [79], with most of the evidence base originating from survey studies carried out in Australia [62,80], the UK [56,59], and Europe [81,82,83]. Gordon et al. [79] recently reviewed key findings from this literature, reporting critical concerns over cost barriers, very limited knowledge or awareness of hydrogen, and major concerns over the disruptive impacts of the hydrogen switchover [54,58,84,85]. The literature suggests the financial costs of hydrogen appliances will determine acceptance levels for most end-users [79].[9] Whether compared to other technologies [58,86] or studied in isolation [55,56,62,87], evidence suggests moderate levels of consumer support for low-carbon, domestic hydrogen.

Notably, Bögel et al. [82], and more recently, Sovacool et al. [70] conducted large sample, cross-country comparative studies. Based on a dataset of seven European countries ($N = 7148$), Bogel and colleagues [82] found that consumer support for stationary hydrogen systems for home heating and electricity was slightly more positive than general attitudes towards hydrogen fuel cell technologies. In contrast, based on a larger dataset ($N = 10{,}109$) spread close to equally across five European countries (Germany, Italy, Spain, Sweden and the UK), Sovacool and colleagues [70] found that just 11 % of respondents favoured adopting hydrogen heating in the next few years, compared to 32 % for solar, 28 % for gas and 20 % for heat pumps [70]. Thus, domestic hydrogen acceptance will depend on whether it is presented as a direct replacement for natural gas appliances or framed as one of several low-carbon technology alternatives.

Beyond these examples, most studies have relied on a single country context and in some cases comparatively small sample sizes [79]. National case studies lend themselves to exploring specific aspects of domestic hydrogen acceptance to derive context-specific findings [87], but are not always generalisable to other country contexts. Small sample studies may also prove limited in their scope to inform decision-making in a specific national context. Studies with a qualitative component have been limited to a few publications, mostly in the grey literature [54,84]. When focus groups have been employed, this method has often been selected to complement quantitative methods [58,85,86]. Principally, focus group data offers added value when implementing a sequential exploratory mixed-methods research design [88,89], wherein qualitative findings are validated by robust quantitative evidence [90].

2.3. Internalising the duality of the residential decarbonisation

Accounting for a lack of engagement with cooking technologies [52] within the discussion of low-carbon futures [79], Scott and Powells [59,60] shifted the discussion of a hydrogen home towards a more balanced level of interest in heating and cooking. Recognising the interactions between these respective sides of the domestic energy transition, Scott and Powells [59:2] advanced *a new social science research agenda for hydrogen transitions*; accounting for the ways in which hydrogen will constitute "new meanings and materialities" into daily practices of cooking and heating. Accordingly, cooking and heating practices are characterised by a complex socio-material nature [60,65],

[7] For example, behaviours and practices may be shaped by social expectations and relational dynamics, parental responsibilities, caring for pets, animals, plants (zoophilism), and underlying efforts to ensure wellbeing in terms health, harmony, comfort, or pain prevention [65,66].

[8] For example, compared to just 48 % in Sweden.

[9] Olympios et al. [226] recently modelled the cost-competitiveness of domestic electricity- and hydrogen-driven technologies from both a homeowner's and whole-energy-system perspective, reporting that hydrogen-driven absorption heat pumps [227] would be a competitive alternative to hydrogen boilers when considering total system transition costs in all hydrogen-pathway scenarios.

which reflects the richness of domestic lifestyles and homemaking practices [91].

Adopting a social practice theory approach [92,93], Scott and Powells [60:3870] further examine how "the physical and chemical properties of hydrogen may disrupt domestic practices of cooking and heating." Foremost, respondents perceived significant changes to the lived experience of cooking (i.e. hob practices) [60]. It follows that social and behavioural aspects of the domestic energy transition [94] should be understood in sync with technical and logistical challenges to support the deployment [54] and social acceptance of hydrogen home appliances [79]. This approach is especially pertinent given that most techno-economic models fail to take consumer heterogeneity into account [35], while justice and equity concerns are equally overlooked [95].

2.4. Fuel poverty pressures and energy vulnerabilities

Critically, fuel poverty pressures have been exacerbated by the COVID-19 pandemic [96] and the latest international gas crisis [97], in turn affecting consumer engagement in energy markets and energy practices [95,98]. Energy poverty levels in the UK increased nearly 50 % between October 2021 and October 2022, reaching an estimated 6.7 million households [98]. Foremost, the effects of energy poverty fall disproportionately on households with the lowest incomes and least efficient homes [98]. Regarding energy vulnerability, disabled individuals are more prone to facing fuel poverty and more likely to be on prepayment meters, which has a multiplier effect on costs, insecurity, and disconnection rates [99]. Rates of fuel poverty and disability vary according to household composition and socio-economic variables, highlighting the multi-dimensional and heterogenous nature of energy vulnerability [99]. Gillard et al. [100] further highlight how disabled people, older members of society and low-income families must contend with multiple energy injustices and vulnerabilities. In response, researchers have called for further scholarship examining "the heating phenomenology of vulnerable consumers" [65:12].

Encouragingly, the hydrogen futures literature is gradually beginning to internalise notions of equity and justice with emerging studies on the hydrogen economy value chain [101], hydrogen-based steel production [102], hydrogen imaginaries in the Netherlands [103], and green hydrogen projects in the Global South [104], including case studies on Morocco and Namibia [105]. In the residential context, consumers appear more preoccupied about the potential running costs of hydrogen appliances than purchasing costs, especially when already facing fuel poverty [56,59]. However, it is probable that ongoing cost hikes in energy bills have shaped this preoccupation, which contrasts against the findings reported in Chapman et al. [69]. Evidently, disruptive trends in energy markets further explain divergent attitudes towards respective costs factors over time.

2.5. Socio-technical imaginaries and the hydrogen futures discourse

Jasanoff and Kim [106] introduced the notion of *socio-technical imaginaries* in 2009, operationalised to a comparative examination of nuclear power in the United States and South Korea. The original definition corresponded to the attainment of desirable futures, expressed as "collectively imagined forms of social life and social order reflected in the design and fulfilment of nation-specific scientific and/or technological projects" [106:120]. More recently, Sovacool and Hess [107:719] highlighted the 'instrumental' and 'futuristic' qualities of socio-technical imaginaries, in terms of projecting "visions of what is good and worth attaining." Moreover, socio-technical imaginaries cut across multiple theories and concepts (see Fig. 5 in [108]), which has seen understanding and application of the term evolving across the social sciences literature, most prominently in Energy Research & Social Science (ERSS) Journal [108].

Interestingly, the notion of visions (or imaginaries) for a sustainable hydrogen future predates the conceptualisation put forward by Jasanoff and Kim [106], and can be traced back to at least 2006 [12], which coincided with a 'mini-hype cycle' of academic interest in the hydrogen economy [1]. Writing in 2006, Eames et al. [109] and McDowall and Eames [12] focused on the 'socio-technological dynamics' of the hydrogen transition, as envisioned by members of the United Kingdom Sustainable Hydrogen Energy Consortium (UKSHEC). Subsequently, the lead authors consolidated the theme of hydrogen futures [64,63], as reflected by Sovacool and Brossmann's [110] examination of visions and imaginaries for the hydrogen economy. As noted by Trencher and van der Heijden [111:210] "the hydrogen society agenda actively exploits rhetorical visions, narratives and imaginaries."

While socio-technical imaginaries have an explicit focus on desirable outcomes [107,111], or "the collective visions of the future and progress" [108:222], visions for low-carbon energy futures entail a more contested dimension [109]. Nonetheless, the parallel focus shared between each umbrella term (i.e. socio-technical imaginaries and visions) is apparent, and should be borne in mind when exploring low-carbon energy futures. To this point, the study of Trencher and van der Heijden [111] engages with national and local imaginaries associated with the Japanese hydrogen transition, with a focus on elements of contestation and concurrence among key renewable energy stakeholders (more aligned to the visions literature). However, to the authors' knowledge, the energy transitions literature is yet to engage concretely with visions for domestic hydrogen futures.

Socio-technical imaginaries scholarship on the residential sector has focused primarily on smart home technologies in the European context [112,113,114,115]. In most cases, insights have been gleaned from engagement with experts rather than consumers themselves, with the public typically perceived as "preoccupied with cost and visual aesthetics" [112:44]. Likewise, in the Australian context, Stengers and Nicholls [116] incorporated interviews with smart home industry professionals, offering a critique of the risks related to new energy practices and potential misperceptions of technological convenience, which the lead authors further explored when considering energy practices of the future in Australian households [117]. Against this backdrop, our study makes a novel contribution by integrating consumer visions for low-carbon cooking and heating technologies into the domestic hydrogen futures discourse, as gleaned directly from the perspectives of consumers as opposed to experts or other stakeholders (see Section 6).

3. Materials and methods

3.1. Focus groups as an instrument for qualitative analysis

Recent contributions to the hydrogen futures literature [61,118] attest to the value of the focus group approach, as a powerful tool for examining public perceptions and social acceptance of emerging energy technologies [119]. Despite limitations in terms of potential self-selection and moderator bias [120,121], as well as digital exclusion [122], focus groups provide an efficient and reliable means for gauging information on novel subject matters through collective interactions [119,123,124,125], while enabling the researcher to identify similarities and differences between participant's responses [123,126]. By facilitating freedom and flexibility, the focus group format encourages participants to arrive towards "new insights and priorities" in the process of shaping the discussion [119:280].

3.2. Recruitment process and focus group categories

Between February and April 2022, the research team conducted 10 semi-structured online focus groups with participants living in the UK

Table 1
Overview of focus groups, February–April 2022.

Focus group	Focus group category	Sample size	Recruitment method
FG1	Moderate interest in renewable energy and in joining a renewable energy community	$N = 5$	Networking with members of the local community
FG2	Strong interest in renewable energy and in joining a renewable community	$N = 6$	Networking with members of the local community
FG3	Owners of solar PV panels and multiple smart home technologies	$N = 3$	Market research company
FG4	Actively engaged in environmental issues	$N = 3$	Market research company
FG5	Living in an industrial city or town	$N = 5$	Market research company
FG6	Living in fuel poverty or facing high levels of fuel stress	$N = 3$	Market research company
FG7	Baseline group (none of the above categories)	$N = 6$	Market research company
FG8	Actively engaged in environmental issues	$N = 9$	Social media platforms
FG9	Owners of solar PV panels and multiple smart home technologies	$N = 8$	Social media platforms
FG10	Living in fuel poverty or facing high levels of fuel stress	$N = 10$	Social media platforms

Source: authors' design.

($N = 58$),[10] as shown in Table 1. The groups were purposively selected to ensure a diversity of participants, representative of specific consumer segments (see Table A1). Each category was deemed to be of primary interest to the research topic. Effectively, a socially acceptable transition to hydrogen [127], or other forms of low-carbon energy, will need to engage with potential early adopters [128,129] and demographic groups impacted by fuel poverty [130,131,132,133], as well as environmentally engaged consumers [134,135].

In each case, a Qualtrics survey was designed to match the recruitment aim. The first acceptance criteria included answering yes to the following question: *Do you currently use a gas boiler*? All participants responded *yes* to this question, while for the follow-up question concerning use of a gas hob, most participants answered *yes*. During the focus groups, a minority of respondents clarified that they had previously used gas cooking but were in the process of switching or had already switched to an electric hob. This nuance enriched the discussion around domestic cooking technologies. Other acceptance criteria are outlined in Table A1 and Supplementary Note 1.

Participants in the first two focus groups were recruited through networking with members of the local community in Marston Moretaine,[11] a village located nearby to Cranfield University, Bedfordshire. In addition to being easily accessible to the research team for networking purposes, this location was chosen in view of its engagement with renewable energy (RE), sustainability and environmental conservation [136,137]. The first group composed of participants with moderate interest in RE and in joining a RE community ($N = 5$), which served as a pilot for the study.[12] All responses and interactions recorded during the pilot matched the quality of other focus groups and the expectations of the research team, therefore, this data was deemed suitable for inclusion in the analysis. The second group from this area composed of participants with strong interest in RE and in joining a RE community ($N = 6$).

A market research company was employed to recruit participants for Focus Groups 3 through 7 ($N = 20$). Owing to a higher than anticipated drop-out rate, usually attributed to participants reporting COVID-19 symptoms, three additional focus groups were organised to fulfil the intended research design. In this case, participants were recruited through social media platforms, which proved effective for consolidating the final sample size ($N = 58$). Three specific categories were targeted during this round of focus groups (April 4–6): owners of solar PV panels and smart home technologies; individuals actively engaged with environmental issues; and citizens living in fuel poverty or facing high levels fuel stress. Based on the preliminary results, it was judged that owners of solar PV panels and smart home technologies served as a close proxy for those interested in RE and with desire to join a RE community (FG2). These sessions (FG8, FG9 and FG10) consolidated the previously underrepresented groups (FG3, FG4 and FG6). Reflecting the spatiality of the UK hydrogen transition and its link to industrial clusters, we also recruited participants from industrial cities and towns ($N = 5$). Finally, Focus Group 7 ($N = 6$) served as a 'Baseline Group' (filtering out all other focus categories) to help facilitate a potential reference point for the subsequent multigroup analysis (see Section 5.3).

3.3. Socio-structural variables

Socio-structural factors [138] include socio-demographic, socio-economic and socio-cultural characteristics [79]. Stringent filtering methods were applied throughout the survey design to ensure targeted recruitment. Quotas were set for gender and age[13] (see Table 2) to ensure a more balanced representation across the final sample. The gender quota was mostly satisfied, with a slight overrepresentation of males. However, the age quota proved harder to meet, with a significant over-representation of respondents aged 26–35, as well as under-representation of respondents older than 65. In terms of housing type and tenure, the final sample was loosely nationally representative of housing type, but less representative of housing tenure, while the average number of occupants per dwelling was somewhat higher than the UK average.

Steps were also taken throughout the recruitment process to ensure the sample covered a range of areas with location quotas set for four groups (FG5, FG6, FG7 and FG10), which accounted for approximately 40 % of the final sample. In addition to the selection of participants from Marston Moretaine, Bedfordshire ($N = 11$), approximately 34 % of the remaining sample was clustered around two locations, namely, Manchester ($N = 9$) and London ($N = 7$). Participants from Manchester and other areas of the North West of England and North Wales are situated in vicinity to the HyNet industrial cluster [139]. Together with the East Coast Cluster [23] – linking Teesside and the Humber – these respective areas were approved for Track-1 government funding in October 2021, as part of the Carbon Capture, Utilisation and Storage (CCUS) Cluster Sequencing Process [140].

The sampling strategy reflects the importance of potential synergies between the Ten Point Plan for a Green Industrial Revolution [46][14] and the UK Hydrogen Strategy [11], which focus strongly on sector coupling [32] and industrial clusters [141]. Admittedly, the final sample lacked additional representation from Wales or Scotland, and moreover, the East of England (see Supplementary Fig. 1), which should be addressed in future research.[15] Overall, while parts of the sample were relatively

[10] Participants received a cash payment of £40 or equivalent Amazon voucher as an incentive.

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

[12] Foremost, the research team tested the suitability of the Topic Guide, alongside the overall structure and duration of the focus group.

[13] For gender, we set an equal quota for male and female. For age, we set higher quotas for ages 25–55 to ensure our sample requirements could be met. Overall, the final recruitment process prioritised inclusion of a representative age sample, as feasible.

[14] See Point 2: driving the growth of low carbon hydrogen, and Point 8: Investing in carbon capture, usage and storage.

[15] Recruitment excluded Northern Ireland.

Table 2
Composition of sample population compared to UK population for socio-structural variables.

Socio-structural variable	Categories	Sample population (%)	UK population (%)
Gender	• Male	53.4	51.2
	• Female	46.6	48.8
Age	• 18–25	3.4	9.4
	• 26–35	36.2	13.4
	• 36–45	17.2	14.0
	• 46–55	20.7	13.7
	• 56–65	15.5	11.7
	• 65+	6.9	16.5
Housing tenure	• Owned outright	48.3	36.0
	• Owned with a mortgage or loan	41.4	27.0
	• Privately rented	6.9	19.0
	• Rented from a housing association or local authority	3.4	18.0
Housing type	• Bungalow	9.0	9.0
	• Detached house	24.0	18.0
	• Flat or apartment	21.0	21.0
	• Semi-detached house	24.0	25.0
	• Terrace house[a]	22.0	27.0
Number of occupants per dwelling	• Six	5.2	n/a
	• Five	12.1	n/a
	• Four	22.4	n/a
	• Three	20.7	n/a
	• Two	27.6	n/a
	• One	12.1	n/a
Average number of occupants per dwelling		3.1	2.4

[a] 12 % of participants lived in end-of-terrace houses and 10 % in mid-terrace houses.
Source: authors' compilation based on data from 2017 to 2020 [142,143,144].

representative of the national population, we encountered limitations in retrieving a fully representative sample, as reflected by the inherent constraints of a research design targeting a small number of focus group participants and categories [95].

3.4. Focus group format and topic guide

Each focus group ran for approximately 90 min and maintained the same structure around a set of specific topics, as described in Table 3. The same moderator led each focus group, with support from research colleagues.[16] Following a brief introduction by the moderator about the guidelines and format, participants gave their consent for recording the session. Throughout the session, participants were probed with follow-up questions to give more specific details and explanation for their views. For the most part, participants proved very forthcoming with information on each technology and required minimal prompting.

Parts 1a and 1b of the topic guide (gas cooking and gas heating) provide the qualitative data for engaging with the first research question, while Part 5 (willingness to adopt domestic hydrogen appliances and support for hydrogen homes) provides the qualitative and quantitative data for answering the second and third research questions. Drawing on the answers provided in Part 2b, insights from these strands are merged to address the final research question concerning cooking and heating technologies of the future. Taken together, the data analysed in this study represents approximately 30 % of the focus groups dataset.

Statements from Part 2a on climate change and the environment

[16] Working at Cranfield University's School of Water, Energy and Environment (SWEE).

Table 3
Overview of focus group topic guide and format.

Section	Theme	Questions and discussion topics
Part 1a	Gas cooking	• What do you like most about cooking on a gas hob? • What do you dislike about cooking on a gas hob? • What would a better cooking system look like in terms of future improvements and upgrades?
Part 1b	Gas heating	• What do you like most about having a gas boiler? • What do you dislike about your gas boiler? • What would a better heating system look like in terms of future improvements and upgrades?
Part 2a	Climate change and environmental issues	• What are your views about climate change and the environment? • How do you think the UK is doing compared to other countries in tackling climate change? • What actions do you take to help the environment?
Part 2b	Low-carbon technologies for cooking and heating	• Can you tell me more about some alternative technologies for heating and cooking? • Can anyone share some information about hydrogen? • What are your sources of information about hydrogen?
Part 3a	Formal introduction to hydrogen: Information provision round 1 (PowerPoint slides and Video 1) and poll question	Poll Question 1: • How do you feel about the government's twin-track approach, with a role for both blue and green hydrogen? (Measured on a five-point Likert scale: Very opposed–Very supportive)
Part 3b	Initial perspectives on hydrogen	• Please can you explain your answer to the poll – what are your initial feelings about hydrogen?
Part 4a	Trust levels in key actors and stakeholders of the UK hydrogen transition: Information provision round 2 (Video 2 and PowerPoint slides)	• 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?
Part 4b	Community benefits, costs, and risks of the hydrogen switchover: Information provision round 3 (PowerPoint slides)	• 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?
Part 4c	The disruptive impacts of hydrogen homes and energy vulnerabilities	• How long would you be willing to be 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?
Part 4d	Choices and decisions regarding energy suppliers, appliance brands and models	• Has anyone changed their energy supply 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?
Part 4e	Cost factors around 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

(*continued on next page*)

Table 3 (*continued*)

Section	Theme	Questions and discussion topics
		when it comes to maintenance of your appliances?
Part 5	Willingness to adopt domestic hydrogen appliances and support for hydrogen homes	Poll Question 2: • How would you feel about switching to a hydrogen hob? (five-point Likert scale: Not willing at all–Extremely willing) • How would you feel about switching to a hydrogen boiler? (five-point Likert scale: Not willing at all–Extremely willing) • Overall, how do you feel about switching to a hydrogen home with both a hydrogen hob and boiler? (five-point Likert scale: Very opposed–Very supportive) • Please can you explain your answers to the poll?
Part 6a	Critical messages for key stakeholders	• Imagining a future where you have to choose about using hydrogen, what would you like to know most of all before making a final decision?
Part 6b	Overall support level for domestic hydrogen	Poll Question 3: • Overall, how do you feel about hydrogen homes being part of the UK's energy future? (five-point Likert scale: Very opposed–Very supportive) • Please can you explain your answers to the poll?
Part 7	Summing up and conclusion	• Do you have any final comments on tonight's topics or key reflections?

were transcribed, wherein the sample demonstrated a moderate level of awareness about these issues for the most part [145]. Notably, Part 2b provided an opportunity to verify if participants had pre-existing knowledge of hydrogen and in what context they were familiar with the technology, if at all. Across the sample, only five participants proved moderately knowledgeable about hydrogen, usually attributed to an engineering or teaching background [146]. This concluded the first part of the session, enabling the moderator to formally introduce hydrogen as the main topic of the focus group. Thereafter, findings from Parts 3, 4, 6 and 7 of the topic guide are reported in respective analyses on socio-political and market acceptance for domestic hydrogen [147], and public perceptions of the twin-track approach and domestic hydrogen futures [146].

3.5. Information provision materials

Information provision materials, consisting of PowerPoint slides and short videos, were incorporated into the session to help establish a basic knowledge level about hydrogen and its emerging applications for decarbonisation (see Table A2 and Supplementary Note 2). These materials adhered to the UK context in line with the research framing. The first video, aired by Channel 5 News on August 17, 2021 – coinciding with the release of the UK Hydrogen Strategy – presents largely pro-hydrogen perspectives from industry and government, conveying a sense of optimism and realism. Additionally, a scientific perspective from Greenpeace cautions of potential risk factors linked to hydrogen:

> The government needs to manage this whole process extremely carefully to ensure that we're not locked into high emissions that other countries aren't interested in and actually become something of a drag on UK [net-zero and energy security] ambitions (Dr. Doug Parr).

The news segment ended with details of the hydrogen blending trials taking place in the North of England, specifically at Gateshead [148,149]. However, the name of the project – HyDeploy – or any other projects in the pipeline went unmentioned [150,151].

The subsequent video was largely impersonal, featuring a brief demonstration of a hydrogen thermostat by Northern Gas Network's Hydrogen Programme Director (Tim Harwood). This video segment can be considered on the one hand as a promotional piece for hydrogen homes, but on the other hand, for newcomers to hydrogen it presents a relatively neutral (i.e. unemotional) overview of domestic hydrogen appliances, as demonstrated at the test site in Gateshead. Foremost, the video was restricted to captions exclusively, which minimised its potential emotional influence.

3.6. Data analysis

Following examples in the energy transitions literature [61,119,152,112], focus group recordings were transcribed and inductively coded on a statement-by-statement level in NVivo12 qualitative data analysis software, [153], thereby, preserving a full account of the collected data [154]. The initial coding procedure provided an effective means for exploring the textual data and processing it into distinct nodes and sub-nodes [155]. Thereafter, we screened these items for validity and reliability, while identifying areas of concurrence and divergence in the data. Following this process, the next stage involved systematically reorganising the retrieved themes through subsequent manual coding, making for a robust two-stage coding procedure [156]. Taken together, these methods reflect the iterative and non-linear process of thematic analysis [157], which provides a means for detecting and identifying factors which explain participant observations [158]. Thereafter, we conducted an interpretive qualitative content analysis [159,160], as a means for systematically organising and quantifying participant statements according to emergent themes and sub-themes [118,161].

To help transmit the focus group data, illustrative quotations are provided to capture participant observations, alongside summary tables [61,95,162], which create a sense of 'narrative weaving' within the analysis [89,118,163]. In parallel, we undertake a multigroup analysis of consumer attitudes towards hydrogen homes by evaluating descriptive statistics from poll results. Taken together, the qualitative and quantitative results contribute towards a mixed methods data analysis [164,165,166] of low-carbon domestic energy futures (see Fig. 1).

4. Consumer attitudes towards cooking and heating technologies

4.1. Perceived advantages of gas cooking

At the start of each focus group, participants were invited to discuss what they like most about using a gas hob. Around half of the sample ($N = 30$) provided comments regarding the perceived advantages of cooking on a gas stove. A total of seven factors were identified through the coding process, which translated to 53 items across the sample (see Supplementary Note 3). For the most part, the benefits of gas cooking were characterised in terms of controllability and ease of use ($N = 19$) and efficiency and responsiveness ($N = 19$), with 12 participants mentioning both benefits. For example, one respondent explained how "*gas is easy control…can turn it up and down and it responds to whatever I'm cooking*" (F9:1), while a professional chef remarked how "*when it comes to usability, gas is much more controllable and provides instant power*" (FG2:3). One participant reflected how "*with a gas hob, the rings cool down a bit faster and that helps avoid burning compared to electric which retains the heat*" (FG2:1), while another shared their experience as follows: "*I've used a multitude of different cookers and I like the gas hob because it's so quick and responsive, and controllable*" (FG7:5).

Among less frequently cited benefits, respondents highlighted the reliability of gas in the event of electricity cuts, its perceived familiarity, convenience advantages, and space saving benefits. In several cases,

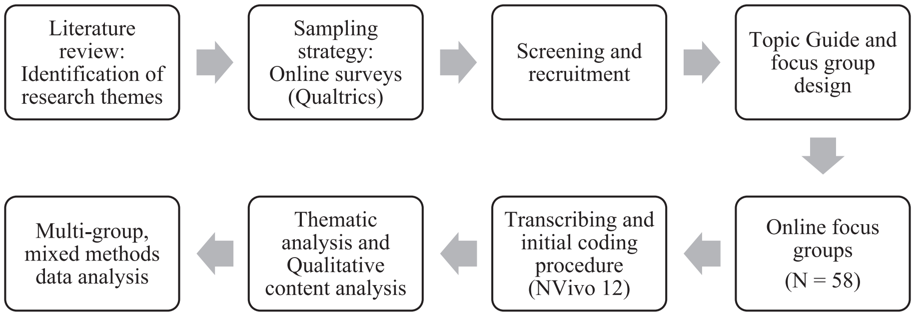

Fig. 1. Research procedure and methodology.

respondents drew comparisons to electric-based cooking appliances to highlight their arguments (see Table 4).[17] For example, one participant described the way in which a gas hob "*holds the heat and cooks quicker and better, and more even*" (FG8:6), while others mentioned how it provides "*good cooking uniformity*" (FG3:2), and "*heats thoroughly and cooks meals properly*" (FG6:2) with "*more consistency*" (FG4:1). Insightfully, a domestic caterer elaborated how the gas stove is an important staple for both their business and family life, "*…with Asian cooking it means we're making lots of chapatis which we can't make on the electric hob*" (FG10:2). In framing this detail, the participant explained how culinary knowhow had been disseminated by their elders. In turn, the low-carbon cooking transition should account for the impact of socio-cultural factors including the passing down of cooking practices between generations [65] and preferences for specific cuisines in order to safeguard against adverse distributional impacts [52].

4.2. Perceived advantages of gas heating

The perceived advantages of gas heating were discussed with a similar response rate to gas cooking ($N = 32$). A total of nine factors were identified through the coding process, which translated to 63 items across the sample (see Supplementary Note 3). Six of the seven factors associated with evaluating the perceived advantages of gas cooking (excluding *cooking consistency and uniformity*) composed the factors identified for heating; reinforcing the overlap between these two aspects of residential decarbonisation.

Mirroring the discussion on cooking, the most cited factor for heating was efficiency and responsiveness. One respondent explained how "*it's much quicker to heat with a boiler…within a few minutes you get heat through the radiators*" (FG2:3), while another commented how "*the new boilers are very efficient which helps a lot too*" (FG3:2). Compared to the discussion gas cooking, controllability and ease of use received less (direct) mentions ($N = 5$). One respondent described their combi boiler as "*very quick, reliable and easy to use…it's just there and ready to use with an easy switch*" (FG7:3). Another participant elaborated on the perceived advantages in more detail: "*If you look at central heating, it's pretty efficient in the fact that it's controllable and warms up the home pretty rapidly. The controllability and speed of response of the gas boiler is good*" (FG3:1). The observed discrepancy between statements on controllability and ease of use for each technology may be accounted for by the associated benefits of gas boilers, which include reliability, convenience, and quiet performance. In this respect, when accounting for indirect references, controllability and ease of use received more attention than efficiency and responsiveness ($N = 23$), as illustrated in Fig. 2.

In terms of reliability and convenience, one participant noted how "*Combi boilers deliver hot water all the time on-demand*" (FG7:1), while another respondent explained how "*you've always got constant heating and hot water which is what you want. It's just convenient, I guess*" (FG4:1). Relatedly, one participant described their gas boiler as both "*convenient and quiet*" (FG1:1). Additionally, regarding the discrete nature of

Table 4
Consumer perceptions regarding the perceived advantages of gas cooking and gas heating.

Perceived advantage	Illustrative quotations	
	Cooking	Heating
Controllability and ease of use	• *My mum has an electric hob which I hate because things start boiling over and it takes ages to bring down the temperature to control it* (FG7:6). • *With the electric hob, you have dials with numbers and need to know what level you want the hob on. Whereas with gas, you just rely on the flame* (FG8:7)	• *Yeah, I think you've got more control, haven't you? Whereas with electric heaters, they seem to take a lot longer to heat up* (FG6:1).
Convenience	• *The gas hob is really convenient and ready to go whenever you want* (FG3:3). • *It's quick, easy and convenient and much better than electric I would say* (FG5:2).	• *The combi boiler is great and convenient, and there's no need for a storage tanker. It's more useful for homes, quicker, more efficient, and very easy* (FG10:3).
Efficiency and responsiveness	• *I like the efficiency of a gas hob. Electric is slow to warm up food. I've switched from electric to gas because I find it much more efficient* (FG6:2). • *You get accustomed to gas, whereas with electric, if you're using a wok and need to reduce the heat, it doesn't really respond* (FG8:3).	• *I prefer gas over any other form of heating because it's quick and the rooms are heated in a matter of minutes* (FG5:2). • *Combi boilers provide hot water as soon as you turn the tap on, while not losing heat in a tank…if you're not using it or you've gone away for the weekend* (FG9:2).
Familiarity	• *I find cooking on gas much quicker and easier. It's something I've done all my life. I've never actually owned an electric hob. My mum had one and she didn't enjoy it* (FG10:3).	• *My parents had it, so when I moved out of the house and got married it was what I knew. I'm familiar and grew up with it* (FG1:2). • *Gas boilers are ubiquitous and the choice for most…if they have the option, then they use it – maybe 90 % of people* (FG8:2).
Reliability	• *With gas, you still have something to use if there's no electricity due to power cuts* (FG2:2).	• *With new technologies that haven't been tested fully, well, what is the lifespan of those new devices like heat pumps or other alternatives? They haven't been around for long enough, but gas is tried and tested* (FG5:1).
Space savings	• *It fits nicely into the kitchen and doesn't take up too much room* (FG3:3).	• *Gas is pretty discrete and hidden away* (FG3:3). • *My boiler is in the loft, so you literally never see it* (FG9:2).

Source: authors' design.

[17] For a comparative review of cooking technologies (gas and electric), see Table 2 in Khalid and Foulds [52].

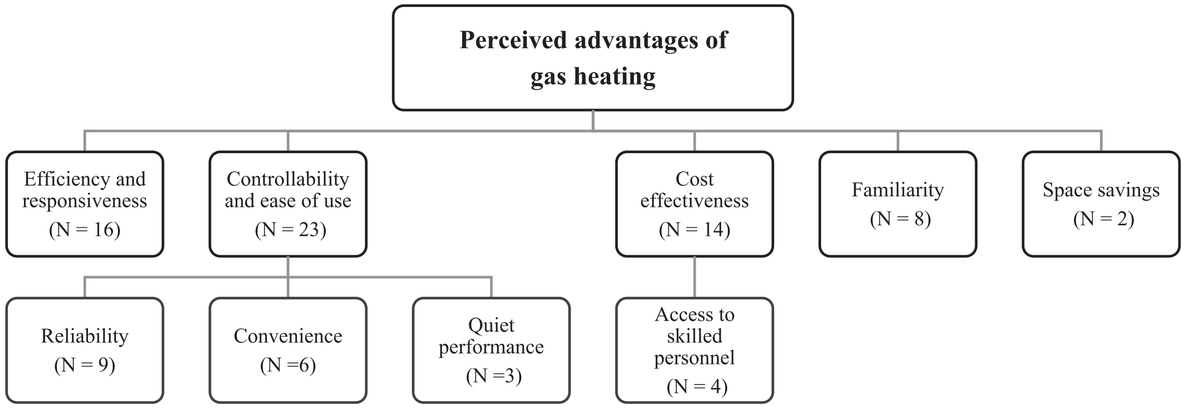

Fig. 2. Breakdown of identified themes and sub-themes regarding the perceived advantages of has heating.
Dark blue rectangles represent sub-themes of controllability and cost effectiveness, which received five and ten direct mentions, respectively.

modern boiler appliances and space saving benefits ($N = 2$), one participant explained how "*you can have a boiler in cupboard which you don't really hear, it sits there, and you don't notice it, which is a good thing*" (FG3:3). Taken together, the above features contribute towards higher performance and lower effort expectancy, thereby relating more broadly to ease of use. These observations mirror recent findings regarding the socio-material nature of boiler practices, which can be seen as largely 'detached', 'invisible', and 'backgrounded', compared to hob practices, which are more 'intimate', 'visible', and 'foregrounded' [60].

Notably, the performance advantages highlighted by respondents reflect the mandating of condensing boiler models for all new installations, as enforced since April 2005 through the Building Regulations amendment [167]. Relatedly, access to skilled personnel for installation and maintenance also emerged a sub-theme, which implies cost effectiveness. For example, one participant described gas as "*tried and tested…if something does go wrong with it, there's always going to be gas engineers available with experience*" (FG5:1), while another commented to the same effect, "*you have so many people out there that can easily change and maintain your gas boiler*" (FG2:5).

Aside from efficiency advantages, factors linked to cost and familiarity featured prominently in the discussion. Regarding cost effectiveness, participants noted how the "*the gas boiler is probably still the most cost-effective* [technology]" (FG5:3), while "*the combi boiler is the best solution…electric heating is currently very expensive compared to gas*" (FG10:2), with gas also being "*significantly cheaper to run if you're having mains gas*" (FG9:2). In terms of familiarity, one respondent framed the positive legacy of gas boilers in the UK:

> *I grew up with coal fires where the heat remained in one place to begin with and we also needed a paraffin heater upstairs and little electric fan heaters, so we had different kinds of heating throughout the whole house. For me, the gas boiler is ideal* (FG5:2).

Echoing these sentiments, another participant shared their experience as follows: "*Gas cooking is what I was taught, what my parents had and what I learnt to cook on, so it was just that continuation…it's much easier and what I've always used*" (FG8:7).

Overall, consumer attitudes towards gas heating reflect findings in the literature, reporting high levels of customer satisfaction due to natural gas boilers fulfilling the following key requirements: high levels of thermal comfort, responsiveness, convenience, and familiarity [168]. Indeed, thermal comfort is typically viewed as the critical factor in determining the adequacy of indoor environments [169]. Additionally, the results demonstrate the extent to which consumers value the socio-material nature of gas heating, as a discrete product and service, while also prizing access to reliable maintenance services.

4.3. Summary of findings on perceived advantages of gas cooking and heating

To conclude this part of the analysis, Table 4 presents a selection of illustrative quotations from the dataset concerning the perceived advantages of gas cooking and heating, with an emphasis on comparisons to electric alternatives, while Fig. 3 compares the number of responses between the six themes identified for both technologies.

4.4. Safety perceptions of cooking technologies

The safety aspects of domestic cooking weighed heavy on the mind of several participants, with close to one-third of the sample contributing to this part of the discussion. However, the debate was considerably one-sided, with only two respondents highlighting the perceived safety benefits of gas cooking. One participant argued in favour of gas as follows: "*From a safety point of view, you can see what you're doing. Whereas with electric, kids are at a greater risk of sticking their hands on a hob that's still hot. That's less likely with a flame*" (FG8:3). In the words of another participant, "*gas feels like cooking without any kind of hazard*" (FG5:2). One respondent also commented on the perceived safety benefits and risks of a gas flame, which drew agreement from fellow participants:

> *Physically, you can see the flame…you've got that visual representation right in front of you, whereas with electric it's pretty difficult to gauge. But the flame can also be a negative, especially when having children in the house since it's quite accessible* (FG6:2).

To the first point, respondents shared similar concerns, with one cautioning how "*…if you have kids at home, you need to be very careful about gas and kitchen activities and watch them carefully*" (FG10:7), while other participants concurred how "*the leaky flame is the biggest risk*" with young children not being able to "*realise the intensity of the heat*" (FG4:1; FG4:3). At the same time, securing the kitchen environment for children was acknowledged as mostly an issue of parental responsibility (FG4:1; FG4:3). To the second point, several participants reliant on old cooking systems and facing fuel poverty (FG6:1; FG6:2; F10:2; F10:3; F10:6; F10:7) expressed specific concerns regarding the risk of "*gas explosion incidents*" (FG10:2). In some cases, these worries were communicated in terms of fear and anxiety: "*I'm always scared because I don't want the gas to be used too much and for there to be a fire outbreak. I'm scared about the damage it could cause with gas leakage*" (FG9:3). Another participant from the same focus group reinforced such concerns:

> *…our gas hob is always trying to kill us! It has no automatic cut off, so I can be sat in the lounge and suddenly smell gas. It doesn't turn off correctly, so it just scares me a little bit. It's been in the house since we bought it* (FG9:1).

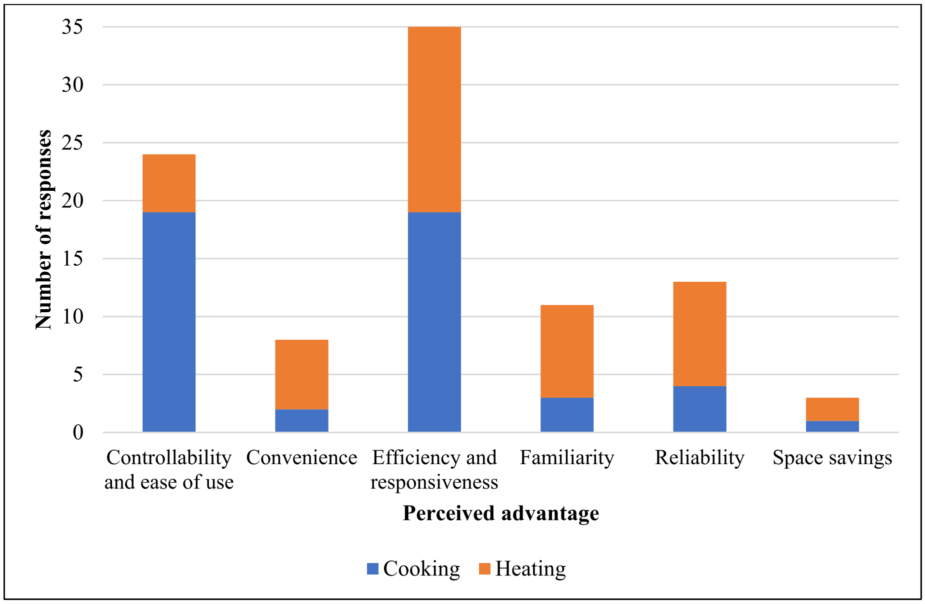

Fig. 3. Distribution of responses regarding the perceived advantages of gas cooking and gas heating.
For gas heating, only direct mentions regarding controllability and ease of use are included, while indirect references to this perceived advantage are reflected by convenience and reliability.

Issues around gas safety were further endorsed by one participant presenting a viewpoint from the fire department:

> *I prefer cooking on electric because of fire safety issues with gas. My husband is a fireman and electrician, and from a safety point of view we tend to find electric a bit safer. An induction hob tells you when it's hot* (FG1:1).

This commentary reminds how the debate around cooking safety may not always be clear-cut and can be highly context-specific, shaped by aspects such as household demographics and appliance condition. Irrespective of household composition, end-user, and appliance condition, other respondents relayed alarming episodes of setting tissues, tea towels or sleeves alight when using the gas hob (FG2:3; FG7:1; FG5:4; FG6:2). Overall, the negative safety aspects of gas cooking revolved around the risks presented by the flame itself, especially to children, and fire hazards caused by leakage. The issue of gas leakage was attributed to leaving the gas on undetected or faulty appliance condition.

In response to concerns voiced over risks and hazards, some participants countered how modern hobs offer safety features, which switch the gas off automatically when the flame is out and prevent the gas from starting up until reignited (FG2:3; FG7:4). One safety conscious participant concluded that "*more sensors are needed for monitoring gas better*," but also conceded to perceiving gas and electric "*as equally dangerous when it comes to burning your hand*" (FG10:3). While safety perceptions may hinge largely on the age and condition of cooking appliances and direct experience, one respondent shared an astute observation which can be generalised nationwide, "*I think the biggest problem is the headlines in the news when someone's house blows up, which is very rare with electric. It's usually gas*" (FG8:2). These comments reflect the ongoing prevalence of gas leakage and explosions [170], which has left some UK communities 'reeling', with safety experts demanding the government to take firmer investigative action [171].

4.5. Perceived disadvantages of gas cooking

Gas cooking was viewed largely positively for its overall performance and mostly negatively in terms of safety, albeit with mixed views which are highly context-dependent. Notwithstanding, five specific themes were identified concerning the perceived disadvantages of gas cooking (see Table 5 and Supplementary Note 3). Interestingly, a minority of respondents regarded electric cooking appliances to hold a relative performance advantage, particularly in the case of induction hobs. For example, one respondent described induction as "*an efficient technology in its own right which gives immediate control, and most of the*

Table 5
Consumer perceptions regarding the perceived disadvantages of gas cooking.

Perceived disadvantage	Total number of responses	Illustrative quotations
Cleaning and maintenance	9	• *I tend to prefer a halogen oven or pizza maker because the gas hob is too much hassle to clean, and stuff gets splattered everywhere. With the others you just take the tray out and stick it under the sink, so it saves time* (FG7:1)
Cost concerns	5	• *Gas is becoming more expensive* (FG3:3) • *Some of these new cookers can be really expensive* (FG5:4). • *The cost of gas installation can be a problem* (F8:3).
Environmental impacts	5	• *I hate using gas for what it is* (FG2:3). • *Gas cooking is not very environmentally friendly* (FG3:3). • *I would have preferred to avoid [a gas cooker] because I don't want to burning stuff basically* (FG8:2).
Efficiency drawbacks	4	• *Condensation is sometimes an issue if you haven't got much ventilation, which wouldn't happen so much using electric* (FG5:1). • *There's a lot of wasted heat with gas cooking which makes it a bit inefficient…it's okay in the winter because it warms up the kitchen nicely but it's a lot of wasted heat in the summer* (FG7:4). • *The gas hob can be a bit of a nightmare during summer because of the ventilation, which is a reason to cook more outside during the warmer months* (F8:3).
Kitchen aesthetics	2	• *Gas hobs look outdated compared to a nice, sleek halogen or ceramic hob which is aesthetically a lot nicer and less clunky* (FG7:5)

Source: authors' design.

electricity that's used to run it will convert into heat, so perhaps there's not as much wastage as with gas" (FG9:2).

Cleaning and maintenance issues emerged as the main disadvantage of gas cooking. Several participants concurred that gas hobs have a propensity to accumulate grease and is cumbersome to clean. Other respondents also drew comparisons to induction hobs which were regarded as "*something you can wipe down easily*" (FG9:2), in stark contrast to the difficulty of cleaning "*the fiddly little burners*" (FG1:3) and "*trying to get into the nooks*" (FG7:2) when dealing with gas hobs. Additionally, one participant further characterised cleaning and maintenance as posing "*the biggest problem*" because "*you have to lift up two heavy grills…so the design is a problem, especially if you are mobility impaired or disabled*" (FG7:1). Overcoming this drawback of traditional gas hobs is critical to alleviating the impact of energy vulnerabilities, which are often overlooked by technology designers and policy makers alike [172,173].

The aesthetics of cooking appliances also emerged as a minor theme of the discussion. Building on the observations around cleaning and maintenance issues, participants further agreed that gas is "*a bit old fashioned*" (FG7:4) and "*cumbersome with styles that are outdated*" (FG7:3). In response, several respondents expressed willingness or preference to move to electric-based forms of cooking such as "*an air fryer or a microwave which has combo for electric grilling*" (FG7:4) or a "*ninja pressure cooker…used for everything except baking*" (FG5:5), which "*…a lot of people are using nowadays as popular replacements*" (FG10:2). One participant went as far to say that "*…it would be better if they made electricity come on at the right temperature and then we would all probably get one* [electric hob], *wouldn't we?*" (FG5:4). This key observation reflects the significantly slower recovery rate[18] of electric cooking appliances, which is twice that of natural gas [52].

Previously, when discussing the advantages of gas cooking, only one participant had mentioned how the affordability of gas over electricity provides "*a significant benefit*" (FG9:2). When it came to highlighting the downsides, one respondent voiced frustration at having to pay £200 to install a gas oven when moving house (FG5:5). Another participant went into detail about how having "*just spent a huge amount of money on a gas cooker…nearly £1000 and over £100 to have the gas connected*" during a kitchen renovation (FG8:2). These costs were deemed unjustified and attributed to a shortage of gas engineers in the South West of England:

> *…for whatever reason where I live, gas engineers are a lot more difficult to come by than electricians…I watched him do it and it's simply push a socket in and turn it. It felt very rude and unfair paying this kind of money for someone who was in the house for about five minutes, but he had to come from a long way away* (FG8:2).

Such experiences reveal how installation and maintenance costs may vary according to both housing design and location, which may result in potentially wide disparities across the UK for consumer charges. Such trends could impact risk perceptions of switching to a new domestic technology, as part of the hydrogen switchover. To support the conditions for a socially acceptable transition, the hydrogen supply chain will need to be robust [1,174], with significant resources allocated towards training a skilled workforce for appliance installation and related logistics [175,176].

The environmental impacts of cooking with natural gas were mentioned sparingly within the wider discussion of negative factors, raised as an issue in just three focus groups (FG2, FG3, and FG8); corresponding to participants interested in RE, and owners of solar panels and multiple smart home energy technologies. The lack of responses could reflect an underlying consciousness, and in some cases explicit knowledge, among respondents that gas heating is the principal source of residential carbon emissions. While appearing a limited priority area for most respondents in this part of the discussion, environmental impacts featured more prominently in the debate around home heating (see Section 4.6).

4.6. Perceived disadvantages of gas heating

Foremost, respondents discussed the perceived disadvantages of gas heating in respect to cost factors and economic concerns. Most concerns and complaints regarding domestic heating revolved around the rise of gas prices and energy costs in the UK, with several participants bringing to life the reality of fuel poverty pressures:

> *I agree that cost is always a concern, and at the moment the price of everything is going up but utilities seem to be starker. I suppose it's something that's harder to control whenever you've got your heating on, even if you've got a smart meter. If it's cold, you have to put the heating on to have your shower or bath. I know you can cut down on these things… but I think the costs for everybody is a big concern* (FG4:1).

In this respect, and as similarly noted by Sovacool et al. [95] fuel poverty pressures have intensified since the time of data collection, which is likely to have exacerbated cost concerns and negative perceptions of the gas industry, while adding to an already pronounced trust deficit in the government and energy companies [147]. Overall, worries over cost factors relate to the purchasing price for boilers, insurance and maintenance charges, the lack of financial support or incentives for low-carbon heating, and most prominently, energy bills, including how they are calculated (see Tables 6 and A3).

Participants also commented on the size, visibility, and noise of gas boilers on a few occasions with somewhat mixed reviews. One participant concluded that "*you get used to the size of a gas boiler if that's all you've ever known*" (FG1:2), while another admitted that the boiler "*can be a bit noisy when the burners start to fire up if you've got one in your kitchen*" (FG9:2). Another respondent expressed dissatisfaction about the noise of their old boiler, which is supposedly "*very efficient*" according to gas engineers (FG6:3). Despite a strong desire to change boiler, this participant remained limited due to a lack of agency, associated with the principal-agent problem [177][19] of living in rented accommodation, which has also been documented by Sandri et al. in the Australian context [61]. Notably, all respondents in Focus Group 6 – living in old properties in the north of England and experiencing fuel poverty – shared similar complaints about the size, noise, and aesthetics of their gas boilers. Although limited to relatively few observations, issues around carbon monoxide poisoning and carbon emissions were also flagged, as reported in Table 6.

4.7. Consumer concerns over electrification

In the process of discussing the drawbacks and shortcomings of gas heating, several respondents drew comparisons to electric-based counterparts, namely, heat pumps and plug-in heaters. The next two subsections review consumer perspectives on each technology.

4.7.1. Drawbacks of heat pumps

Observations regarding heat pump technology were made spontaneously within six focus groups (FG2, FG3, FG4, FG5, FG8 and FG9). When prompted about alternative heating technologies, two other focus groups (FG1 and FG7) also commented about heat pumps. Interestingly, participants experiencing fuel poverty failed to mention any details about heat pumps (FG6 and FG10), which could be attributed to a combination of factors, such as general lack of familiarity with the technology, affordability issues, and unsuitability for installation due to poor thermal performance within the home [47].

[18] The time taken for oil to come back to temperature after uncooked food has been added [52].

[19] Whereby the desires or goals of the landlord (principal) come into conflict with those of the tenant (agent) (see [228]).

Table 6
Consumer perceptions regarding the negative perceptions of gas heating.

Perceived disadvantage	Total number of responses	Illustrative quotations
Carbon monoxide and carbon emissions	4	• *I'd much rather move away from having gas because of fumes and the environmental damage they cause. Also, the danger of explosions* (FG2:3). • *I have various Nest alarms*[a] *around the house because I'm paranoid about carbon monoxide* (FG9:1). • *You are technically burning fossil fuels and creating nothing but* CO_2 *at the other end, so there is an environmental impact on it* (FG9:2).
Cost concerns	8	• *The cost impacts haven't been massive yet, but come April we keep being told that it's all going up, so we're not looking forward to that* (FG1:3). • *The cost has been in the news so much lately and it's going up so much now… you've got to watch the pennies. I am concerned about it you know, so we will be looking at ways to save money on our heating* (FG4:2). • *The worry for a lot of us is the cost of these new forms of heating. It's very expensive, isn't it. The money in the discount scheme is very little compared to the cost of the new heating system* (FG5:4).
Size, noise, and aesthetics	5	• *I absolutely hate how much space my boiler takes up as a huge part of the kitchen, an entire corner! Yes, it's in a cupboard but that space could be better utilised* (FG6:2). • *Yes, same for me as well, but mine's [gas boiler] not in a cupboard. It looks quite ugly. There are pipes going up to it and it's big* (FG6:1). • *We've got a system boiler which is noisy because the water drips from the loft into the tank, and we've got pumps and a normal gas boiler downstairs…and we're about to have all that replaced and moved downstairs because of the noise of it* (FG9:1).

[a] See https://www.plumbnation.co.uk/nest/.
Source: authors' design.

Notably, a retiree lamented how they "*would never get the payback on investing in a heat pump*" (FG5:3), while another respondent of retirement age (FG3:1) drew comparisons between solar PV panels and heat pumps when considering the investment implications. However, most remarks revolved around technical barriers. For example, a solar PV owner from the South West of Scotland reflected on their experience with heat pumps:

We were investigating a few years ago whether to install a heat pump or to get a new gas boiler. Apart from the fact that you need to leave a heat pump on all the time, which is a negative, it also makes quite a lot of noise and depends on the type of house you have. In our case we don't have wall cavity insulation, so it wouldn't work given the size of our house (FG3:2).

Another participant talked pragmatically from their experience in the buildings trade, "*…that's right, it's a passive thing. First, you have to fill the cavity, but older houses need better insulation to make them more efficient to reduce the demand for heating*" (FG2:5). Along these lines, one respondent described heat pump technology as having "*never quite been suitable*" for their current property (FG9:1), while another mentioned how "*heat pumps need much bigger pipework and radiators*" (FG3:1).

A systems engineer elaborated on the problem of technology lag and cost risks:

I do think there's this kind of lag in technology sometimes. I'm in a 1930s house which I'm slowly doing up now, but it's kind of ripping up the floorboards and insulating under it. You have to do it piecemeal sort of thing, while still living in it. But all the time technology is improving. Hopefully, I have the sort of efficiency by the end of the year where I can go for a heat pump, but until they sort of become mainstream, the price is quite high. They are now saying we've reached a point where solar panels have dropped 80 % in price, so you don't want to invest too early. You risk paying a lot more and the technology being less efficient than later systems, when the efficiency and performance of heat pumps improves. But to get those working in an old house, you first have to do a hell of a lot of work! (FG8:4).

Participants with aspirations to join a RE community also agreed with one another that "*heat pumps are too disruptive*" (FG2:4), with one comparing them to electric vehicles in terms of infrastructure barriers and public aversion (FG2:3). Concerns about the reliability and performance of heat pumps were also contrasted against the practical advantages of boiler installation:

Heat pumps are noisy outside, cause lots of vibration potentially and not as efficient in the hardest, harshest of winters when it's minus 10 °C, so you're always going to need a plan B. Whereas with gas, you've already got the plumbing in place normally, so it's a quicker job to get it replaced (FG9:2).

Reflecting some of the underlying scepticism towards the technology, one participant had "*heard that these heat pumps aren't the panacea that people say they are and they're actually quite expensive to run*" (FG7:1). This statement reflects how technologies that are yet to penetrate the market may enter the public consciousness by word of mouth, while remaining largely unfamiliar. By contrast, heat pumps have reached a high level of market penetration throughout Scandinavia, while France and Germany have become European frontrunners [178]. Researchers have found that the unfamiliarity of heat pumps [47] remains a significant barrier to adoption in the UK [58,178], which provides a critical lesson for the diffusion of other low-carbon technologies such as hydrogen.

4.7.2. Drawbacks of electric heaters

All groups mentioned the use of either plug-in electric heaters or experiences with immersion heating. Plug-in electric heaters were disliked due to their inability to heat individual rooms quickly (FG2, FG6, FG9), while three participants from the same focus group (FG7) fixated on the high costs of using immersion heater. One talked about how "*it was total nightmare for cost*" (FG7:3), while another recalled her parents command, "*thou shalt not use the immersion heater*!" (FG7:6), with the third agreeing "*it's still really expensive*" (FG7:5). Another participant relayed her recent experience of ongoing cost challenges:

We had an electric boiler installed last year and it had so many problems and faults that it cost a lot more money, so it was actually cheaper to run a gas boiler over several years than it was to run an electric boiler for one year! (FG1:1).

On this theme, another participant commented that immersion heating "*takes time compared to an instantaneous gas boiler, and the cost to heat that water for an electric is much higher*" (FG8:3). Similarly, one respondent explained how "*gas gives you immediate heat and it's very controllable, unlike storage heaters which would heat in the night, and then you get immediate heat in the morning, but come evening it's all gone away*" (FG9:2). Such observations match findings in the literature, which characterise electric storage heaters as requiring a specific "process of learning through experience" for effective use and management [179].

Insightfully, one participant summarised their take on the available technology options, or lack thereof:

There's not a lot of choice really. You either go for gas or for electric and you have to plan ahead. I've had electric in the past with storage heaters *and you almost have to predict what the weather is going to be in the next few days and turn it on early enough to make sure your house warms up. Going with something else is likely to be very expensive. I'm trying to go with underfloor heating at the moment, but it's a very big move to make* (FG8:5).

Underfloor heating was also mentioned in the first focus group as being "*cosier*" since it "*spreads the heat out more*" (FG1:1). However, according to the same participant, most individual households are constrained in choosing this technology and reaping potential efficiency gains, irrespective of cost factors:

I do think the environmental side of things is at the design level, so if the house is designed to be more energy efficient or the building is more energy efficient, then that's fine. But if you're in an old property with gas central heating, then your kind of limited to a certain extent on how eco-friendly you can be (FG1:2).

In this respect, it is well-documented how the UK faces a domestic energy efficiency crisis [180,181,182,183], owing to a significant part of the population living in houses well over a century old [183,184], which struggle to meet energy efficiency standards [70,182]. The UK has the oldest housing stock in Europe with around 38 % of homes built before 1946, of which 21 % are pre-1919 builds [143]. As documented by Roberts et al. [183], there are approximately 8.5 million 'hard-to-treat' dwellings in Britain (~30 % of the total housing stock), responsible for around 50 % of carbon emissions from the domestic sector [185]. While low-carbon heating technologies continue to develop, implementing available energy efficiency measures – especially for aging parts of UK housing stock and in fuel poor or off-grid areas – should be front and centre of heat decarbonisation strategy [178].

Overall, consumer perceptions align closely to recent survey findings in the UK context, wherein close to 30 % of respondents believed new electric heating technology would fail to heat the home as well as gas, while 41 % considered the running costs of an electric heating system would be too expensive [69].

5. Consumer attitudes towards hydrogen homes

Taken together, the results reported in Section 4 are broadly consistent with previous findings in the literature. Notably, Chapman et al. [69] reported that ease of use, convenience, reliability, and controllability ranked as the most important attributes of gas cooking and heating, whereas electric cooking and heating (sourced from renewables) were regarded as considerably safer and significantly more environmentally friendly [69]. In addition to affirming these findings, this study addresses the limitations of most previous research on the topic (e.g. [52]) by treating cooking and heating as separate entities and undercovering areas of convergence and divergence among key acceptance factors. The next two sub-sections turn attention to the topic of domestic hydrogen acceptance by reporting results from the polls conducted towards the conclusion of each focus group, and the subsequent discussion, in which respondents explained their respective positions.

5.1. Analysis of quantitative data

Building on the comparative analysis and as a means of engaging directly with the domestic hydrogen transition, participants were asked the following poll questions to determine their attitudes towards switching to a hydrogen home:

(1) *How would you feel about switching to a hydrogen hob?*
(2) *How would you feel about switching to a hydrogen boiler?*
(3) *Overall, how do you feel about switching to a hydrogen home with both a hydrogen hob and boiler?*

The third question set out to test whether the proposition of both appliances differs substantially from responses for each technology individually. As discussed here, the results suggest a prevailing tendency of consumer support for hydrogen homes above support for either pathway individually.

The response rates for each poll question were close to 90 %. Consumer willingness to switch to hydrogen cooking and hydrogen heating proved near equivalent, as measured according to a five-point Likert scale (*Not willing at all*, *slightly willing*, *somewhat willing*, *very willing*, *extremely willing*): $M = 3.56$ for cooking, $M = 3.62$ for heating. Firstly, a notable response pattern emerged wherein *not willing at all* registered as a response for hydrogen cooking ($N = 2$), but not hydrogen heating. This distinction was explained by an expressed preference for induction hobs. Next, responses proved near equal for *slightly willing* ($N = 3$, $N = 4$) and moreover, for *somewhat willing* ($N = 19$, $N = 20$), which was the most common answer. Furthermore, responses provided identical for *very willing* ($N = 17$) and *extremely willing* ($N = 9$), showing both the discrepancy between these levels of willingness, as well as consistency among consumer perspectives towards each technology.

Interestingly, when asked about switching to a hydrogen home, as opposed to individual technologies, support levels increased significantly: $M = 4.14$ (1–5: *Very opposed*, *somewhat opposed*, *neutral*, *somewhat supportive*, *very supportive*). Most respondents were either *very* or *extremely supportive* of hydrogen homes, compared to around half being *very* or *extremely willing* to switch to a hydrogen hob or boiler. Regarding less favourable responses to the prospect of a hydrogen home, only five respondents held a neutral view, while a single respondent proved *somewhat opposed* and *very opposed*, respectively.

Fig. 4 visualises these results but uses 'willingness level' for the x-axis to enable a more direct comparison. The subsequent analysis explores distinctions between consumer attitudes towards each pathway, and their views towards the combined prospect of switching to hydrogen appliances. Critically, the qualitative discussion reveals nuance between consumer attitudes towards hydrogen cooking and heating, which may otherwise be overlooked in near homogenous poll results. Additionally, further examination helps account for observed differences which could be partially attributed to divergent scales between poll questions.

5.2. Analysis of qualitative data

Based on follow-up statements, several observations are noteworthy when distinguishing between the two pathways. Firstly, some consumers consider hydrogen cooking as a slightly more attractive option than hydrogen heating, largely owing to a perception that switching to a hydrogen hob is less risky, disruptive, or costly compared to a hydrogen boiler. Additionally, the proposition of hydrogen cookers may prove reasonably popular, or at least acceptable, for most existing gas users. At the same time, it should be noted that a lack of willingness or complete disinterest in hydrogen cooking typically stems from a preference for alternative electric-based options (i.e. induction hobs), which some respondents had already invested in or planned for. In recent years, induction hobs have taken an increased market share in the UK, following their energy efficiency and safety advantages [186]. Accordingly, patterns of technology diffusion for electric cooking [187], both in terms of speed, scale and location [188,189] will also impact the desirability and acceptability of hydrogen cooking across UK geographies and different parts of the housing stock.

When questioned about what would support moving from *somewhat willing* position to a *very* or *extremely willing* position for appliance adoption, respondents mostly cited the need for more information and better understanding about key factors such as costs and safety. For example, one respondent posed a series of questions:

…are they vastly different to gas appliances? And what about safety? Cause right now, you can smell gas and you know it's dangerous if it's left on. Is hydrogen the same, is it explosive, it is dangerous, can you smell it if it leaks somewhere? (FG1:4).

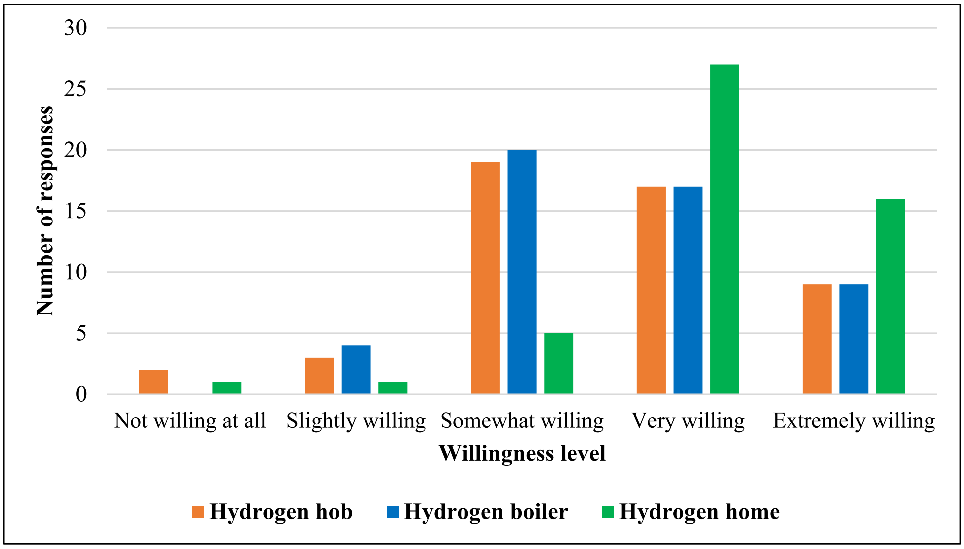

Fig. 4. Consumer willingness to switch to domestic hydrogen appliances and support for hydrogen homes.
Green bars from left to right = Very opposed, somewhat opposed, neutral, somewhat supportive, and very supportive.

Specifically, around one-fifth of participants provided direct explanations for preferring either a hydrogen hob or boiler, or both appliances, which in some cases reflected widespread agreement within groups regarding these preferences.

At the same time, it should be noted that consumer preference in this context does not infer the option of remaining on natural gas for one technology and switching to hydrogen for the other. Foreseeably, a grid conversion to hydrogen would entail a coordinated switchover for both cooking and heating appliances, although hydrogen blending may present an interim step [148,149]. This reality is mirrored in ongoing discussions over whether boiler appliances should be labelled as 'hydrogen-ready' [190] or 'hydrogen-capable' [191], and how such decisions may influence consumer perceptions and protection. This development reinforces the overshadowing of hydrogen cooking in the current discussion. The status quo lends credence to the argument that electric-based alternatives may become increasingly prevalent in UK kitchens, in line with certain consumer preferences expressed in this study.

Based on the evidence presented in Table 7, consumer preferences towards hydrogen cooking and heating were associated with specific justifications. Firstly, a common viewpoint is that a double conversion would help minimise costs and disruption, which may prove a strong selling point for hydrogen homes. Reflecting on costs and disruptive impacts, one solar PV owner framed their willingness as follows:

> *Cost and disruption are what it comes down to for me. How disruptive is it going to be to change appliances and how much is it going to cost…and if the running costs are lower, is it worth changing? It's all to do with finances and the disruption. I'm somewhat willing but need to do more research* (FG9:1).

Secondly, although a notable minority, some respondents prioritised installing a hydrogen boiler over a hydrogen hob due to the greater impacts on carbon emissions reduction. While an exploratory finding given the small sample size, such perspectives are an encouraging signal for the heat decarbonisation agenda. Technology decisions which consider emissions intensity can feasibly become more widespread, as environmental and energy technology engagement grow.

Thirdly, an important aspect of decision-making also revolves around risk perceptions. Consumers may associate greater risks with installing either a hydrogen hob or boiler appliance, according to past experience, perceptions of technology alternatives, and frequency of use. Finally, in terms of frequency of use and reliance on energy services, heating is usually prioritised over cooking. However, assumptions regarding dependency on respective sides of the domestic energy transition must be approached cautiously and evaluated on a situational basis according to socio-demographic characteristics and socio-cultural factors.

5.3. Multigroup analysis of domestic hydrogen acceptance

The main analysis has examined consumer responses across the sample, as a way of understanding preferences for domestic cooking and heating technologies, and willingness to adopt hydrogen-fuelled appliances. To derive additional insights, this sub-section draws on descriptive statistics to compare responses across sub-groups for converting to hydrogen cooking and heating (see Fig. 5), adopting a hydrogen home (see Fig. 6), and across all three measures (see Fig. 7).

Notably, strong interest in RE and in joining a RE community (FG2) aligns with support for domestic hydrogen, ranking first for both hydrogen cooking and heating (+0.68 and +0.61 points above the mean score). Consistent with these findings, this focus group category also ranks second in terms of support for adopting a hydrogen home (+0.32 points above the mean score). By comparison, moderate interest in RE and in joining a RE community (FG1) reduces acceptance levels across all three measures, with willingness to adopt hydrogen cooking and heating falling below the sample average (-0.19 and -0.42), although support for adopting a hydrogen home is marginally higher (+0.17). These results suggest that interest and engagement with renewable energy may increase domestic hydrogen acceptance.

Additionally, fuel poverty pressures may encourage support for domestic hydrogen across all aspects of the transition, with this focus group category (FG6 and FG10) ranking second across the sample for both hydrogen cooking and heating (+0.40 and +0.33) and maintaining a positive attitude towards hydrogen homes (+0.25). Similarly, living in an industrial town or city appears positively associated with domestic hydrogen acceptance, ranking first for the adoption of a hydrogen homes (+0.52), with two participants answering *very supportive* and three responding *somewhat supportive*. For this group (FG5), response patterns were consistent for hydrogen cooking and heating: two participants answering *very willing* and three responding *somewhat willing*. However, for these measures, mean acceptance levels proved comparatively lower in view of the five-point Likert scale (+0.08 and +0.01).

At the negative end of the acceptance spectrum [127], respondents actively engaged in environmental issues (FG4 and FG8) were comparatively less supportive of domestic hydrogen, falling below the mean

Table 7
Consumer attitudes towards switching to hydrogen cooking and heating.

Participant	Views on converting to a hydrogen home	Preference
FG1:2	• *Well, I think if you're doing one you might as well do everything. It all comes down to cost and sort of how easily you can change and what the impact is. But certainly, if I was going to change, I'd change everything.*	Cooking and heating
FG1:3	• *Certainly, if I was going to do it, I would want to do both and have a hydrogen home, not just a hydrogen boiler or hob. No point messing around.*	Cooking and heating
FG2:3	• *I would go for both without a shadow of a doubt. I'm always an early adopter, as long as I could afford it. If you could pay off the costs over three to five years, then it's acceptable.*	Cooking and heating
FG3:1	• *The boiler is the obvious one to hit first in terms of usage. I'd sooner go with the heating…because if anything went wrong with the cooking, there are alternatives. But currently, the main use of gas is central heating and that offers the biggest benefit.*	Heating
FG3:2	• *I think the boiler is most important. You can still have a hydrogen boiler and an induction hob, really. For me, if I'm going to go with hydrogen, especially because of climate concerns, then the boiler is my first priority. That's where I'm using most of the energy in the house; cooking is less and as I said, I wouldn't mind an induction hob. Most CO_2 emissions come from heating.*	Heating
FG3:3	• *I was slightly more willing to go with the cooking to start with because I just think if there was a problem, I could cook with an air fryer or something like that. Whereas the boiler is something I'm more reliant on. So, I might be a bit more reluctant to go all out on it, and rather experiment with the cooking side first.*	Cooking
FG5:1	• *I would go with the cooker first to trial that to see what it achieves, and then possibly moving to the boiler. So, taking a small step to see what hydrogen is actually like.*	Cooking
FG5:5	• *I would probably start with the boiler to make more of an impact because my heating costs a lot more than my cooking, but it would all come down to cost. If you could do the hob cheaper, you might do that first. It depends if there are any programs or incentives to do both at once.*	Heating
FG6:2	• *I'd rather have both than one. It wouldn't make sense to me, having two kinds of appliances running on two different types of systems. It just makes sense switching over everything at once.*	Cooking and heating
FG7:3	• *I feel that if you are having the disruption of a new boiler, then you may as well do both.*	Cooking and heating
FG8:7	• *The cost of getting both will be a lot, so it's better you go with one. The probability of boilers causing problems in homes is very limited. I will prefer to go with the boiler.*	Heating
FG10:8	• *I will need them both but will go for cooking more. I prefer cooking because I cook more often compared to using my boiler.*	Cooking

Source: authors' design.

score for all three respective measures (-0.52, -0.48, and -0.42 for hydrogen cooking, heating, and a hydrogen home). This finding is consistent with supplementary analysis of the focus group dataset, which reported lower levels of support for domestic hydrogen as part of the UK's energy future among environmentally engaged citizens (see Supplementary Note 4). Resistance among this group was partially attributed to concerns surrounding the twin-track production approach (i.e. 'blue' and 'green' hydrogen).

Somewhat of an outlier in this study were owners of solar PV panels and smart home technologies (FG3 and FG9), who fell among the mid-level for hydrogen cooking (-0.19) and hydrogen heating (+0.30) yet ranked bottom for adopting a hydrogen home (-0.75). This result may be partly explained by variation among respondents answering the final poll question and is otherwise attributed to a small sample size ($N = 9$), excluding non-responses. Notwithstanding, subsequent studies should explore the dynamics of RE engagement to validate potential divergence between consumers owning low-carbon and smart home technologies and those expressing a strong preference to join a RE community.

Finally, the Baseline Group (FG7) approximated the average level of support for adopting a hydrogen home (-0.08). This result would suggest that controlling for RE engagement, fuel poverty pressures, and living in industrial areas, may decrease domestic hydrogen acceptance. While explorative given sample size constraints, response patterns reflect potential areas of consumer heterogeneity. Additional focus group data and large sample survey studies are needed to validate these observations, alongside unpacking the implications of low-carbon technology ownership on consumer attitudes towards domestic hydrogen futures.

In light of these findings, an alternative option for exploring the aggregate data and smoothing out some of the results (e.g. in the case where respondents reject hydrogen cooking due to an expressed preference for an induction hob) is to take the average score across all three poll responses (see Table A4). Following this procedure, owners of solar PV panels and smart home technologies rank fifth, above the Baseline Group and citizens actively engaged with environmental issues. The difference between the top-ranking group (interested in renewable energy: FG2) and bottom-ranking category (environmentally engaged: FG4 and FG8) was 0.77 points.

Overall, other patterns remain mostly consistent, with the following groups scoring above the average ($M = 3.73$, $SD = 0.36$): strong interest in RE and in joining a RE community (+0.54), living in fuel poverty or facing fuel stress (+0.33), and living in an industrial city or town (+0.20). By contrast, the following groups fell below the mean score: moderate interest in RE and in joining a RE community (-0.15), owners of solar PV panels and smart home technologies (-0.21), Baseline Group (-0.23), and citizens actively engaged in environmental issues (-0.47). It can be concluded that degrees of consumer heterogeneity may be associated with domestic hydrogen acceptance, which should present a focal point in subsequent research.

5.3.1. Investigating the influence of age on domestic hydrogen acceptance

Following Table 2, which confirmed an overrepresentation of young respondents (below 35 years old) and an underrepresentation of respondents aged above 65, we investigate the relationship between age and domestic hydrogen acceptance (see Table A5). Fuel poor respondents were outright the youngest group, with most participants aged 26–35 years, whereas the industrial towns group, baseline group, and strong interest in renewable energy groups had a diversity of respondents, averaging in the 46–54 years range. Converting respective age brackets (18–25 through to 65+ into a scale of 1 to 6) resulted in a mean score of 3.50 across the sample: falling halfway between the 36–45 and 46–54 years. To calculate the mean score for domestic hydrogen acceptance, we take the average values from willingness to adopt a hydrogen hob and boiler, and support for a hydrogen home (see Fig. 7) and compare the rankings between age (youngest to oldest) and acceptance rank (most to least) as reported in Table A5.

In summary, the results for this small-sample study suggest no clear relationship between age and domestic hydrogen acceptance, following mixed results. While rankings align for the pilot group (FG1) and Baseline Group (FG7), and conform for fuel poor respondents (FG and FG10), all remaining focus group categories present disparate rankings. It is suggested that focus group membership is likely a stronger predictor of domestic hydrogen acceptance, while other socio-structural variables such as income, gender and housing characteristics (e.g. number of occupants per property) may have a stronger moderating effect on acceptance than age. Follow-up studies should seek to validate the statistical effects of respective socio-structural variables on support levels for hydrogen homes.

6. Consumer preferences for domestic energy technologies

To conclude the analysis, this section synthesises the findings to identify consumer preferences for future domestic energy technologies.

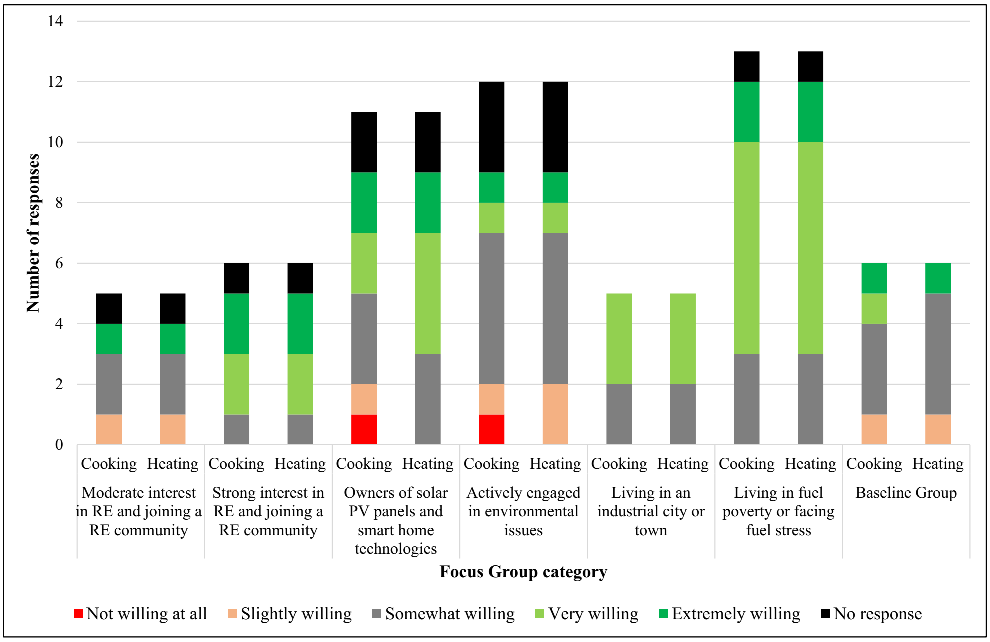

Fig. 5. Consumer attitudes towards hydrogen cooking and heating by focus group category.

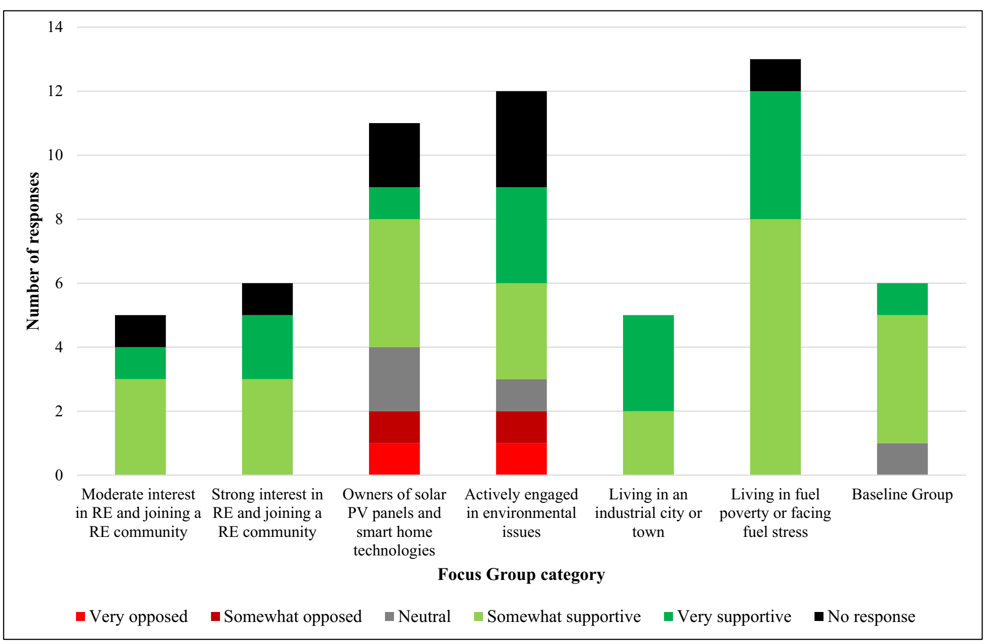

Fig. 6. Consumer attitudes towards hydrogen homes by focus group category.

Section 6.1 engages with future cooking technologies as a way of envisioning priority areas for a prospective hydrogen hob, while Section 6.2 specifies consumer preferences for domestic heating, which can be extrapolated to hydrogen boilers.[20]

[20] In this paper, we make no explicit distinction between 'hydrogen-ready' or 'hydrogen-compatible' boilers – running on natural gas but suitable for converting to run on hydrogen – which are necessary in the initial stages of deployment – and hydrogen-specific boilers. Since our study forecasts for homes of the future, or more long-term deployment, we apply the broader term 'hydrogen boilers' throughout the analysis.

6.1. Consumer preferences for future cooking technologies

Following the discussion on consumer perceptions of cooking appliances, participants were invited to describe improvements or upgrades to a domestic cooking system of the future. Reflecting the wider discussion, one respondent provided a meaningful synopsis:

Going forward, anything that is quick, safe, reliable and clean is probably going to take everything over. At the moment, you can either have electric which is slower but probably easier to keep clean, or gas with instant heat but more safety risks (FG5:2).

Other participants called for a smarter cooking system and more sensors to upgrade safety and overall cooking performance, as well as "*a more contained flame*" (FG6:2). Safety proved a critical concern for

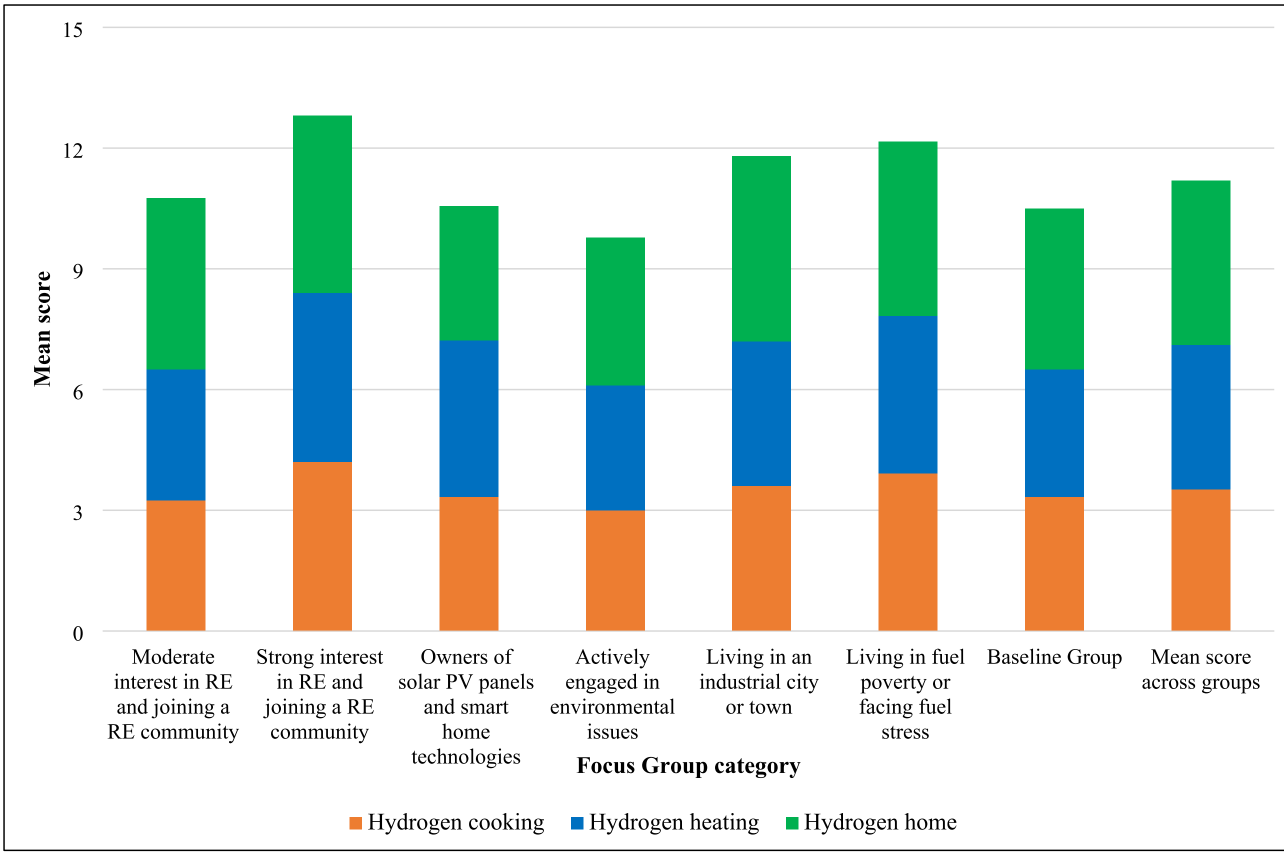

Fig. 7. Consumer attitudes towards the domestic hydrogen transition by focus group category.

consumers facing fuel poverty pressures and reliant on old cooking systems, as well as those with young family members. By contrast, one participant from the industrial towns group framed things somewhat differently:

> …*versatility of the appliance is the number one factor and ultimately the cost of running that appliance. What cost does the new technology bring for that versatility and how is that going to be balanced out*? (FG5:1).

Additionally, a minority of respondents highlighted how cooking practices can be readily handed down between generations [65], in turn shaping attitudes and preferences to current and emerging technologies. In turn, to safeguard against adverse distributional impacts [52], the low-carbon cooking transition should account for the impact of socio-cultural factors including consumer preferences for specific cooking styles and cuisines.

Synthesising the evidence base, consumers envision a future cooking hob that combines the best features of gas and electric, with a growing desire for sleeker aesthetics. When considering the prospect of hydrogen cooking appliances, it can be inferred that safety features should be prioritised alongside smart features to ensure consumers currently reliant on older gas hobs are offered a superior system. It follows that more reliable safety features are especially prized by fuel poor respondents accustomed to older and riskier gas hobs. As technically feasible, steps should also be taken to make hydrogen appliances easier to clean than their natural gas counterparts, while ensuring flame control, cooking performance and reliability are maintained, if not improved.

6.2. Consumer preferences for future heating technologies

The analysis highlights how heating preferences may be driven by multiple factors, especially cost, comfort, and convenience [192]. Furthermore, satisfaction with boiler appliances is highly influenced by the age and design of the system, reflecting the fact that UK homes are populated by a heterogenous mix of gas boilers [48],[21] which mirrors the diversity of an aging housing stock [183]. This reality underscores the potential heterogeneity of residential heat demand [193] and household energy preferences [35]:

> *One of the biggest problems in this country is that we have an elderly housing stock. The house I live in was built in 1907 and it's got solid walls, so you can't do any wall insulation and it's very difficult to insulate the property. The housing stock in this country is so old and inefficient. That's going to be a very difficult problem* (FG7:4).

Notably, one participant reinforced how low-carbon heating remains a systemic problem yet to be tackled in the UK, "*our house is only four years old and very thermally efficient, and we should have a heat pump really, so it's ridiculous we've got a gas boiler. It doesn't make any sense*" (FG2:3). Such observations underline how policy measures to ban fossil fuel boilers from newbuild homes by 2025 are arguably several years overdue.

As a way of gauging consumer desires and expectations for improvements around home heating, respondents were asked about how their domestic heating system could be improved for the future. Two respondents made explicit comments about decarbonising home heating, with one calling for "*a heating system that didn't rely on the use of fossil fuels, but instead something that was much more environmentally friendly*" (FG2:3), while the other called for more "*sustainable opportunities*" but also expressed her reluctance due to a lack of trust:

> *I'm always getting phone calls from services in the local area to upgrade my boiler…all these government grants…we've never actually taken*

[21] See Fig. 9 in [48].

anything on but would be interested to find out more. The problem is every time I get a phone call, I think it's a scam! (FG4:1).

In recent times, similar scepticism and reluctance has often overshadowed an array of "*inducements, instructions, prompts and prods*" designed by UK policy makers to motivate energy efficient home renovations [194]. Other respondents framed their comments around ensuring energy efficiency gains for heating appliances, "*so that you're not wasting energy when you use it*" (FG3:3), and "*looking at the efficiency rating to make sure the boiler's going to perform well*" (FG2:6).

Participants actively engaged in environmental issues suggested smarter monitoring "*to show you how your energy usage is affecting the environment in real-time*" (FG8:9), or using a similar device "*to cut back on energy bills*" (FG8:8). Elaborating on the environmental impact of gas heating, one self-described 'retrofit geek' stressed the difficulty of proper decision making when considering the "*green contribution*" of low-carbon technologies:

> *…what are the facts and the true carbon figures when you consider whether to go from hydrogen, heat pumps or photovoltaics…what are the carbon implications and environmental impacts…you need a balanced approach…to make an informed decision and I find I'm pretty much stuck, even though I work in housing* (FG8:3).

This admission highlights the need for transparency in communicating the lifecycle emissions and carbon footprint of different energy technologies for the home. However, as communicated by the following observation, technology design, resource availability, and user intentions may remain misaligned: "*We've got a new build house which has an eco-channel…and they have also eco-zoned our house…but we still use gas. It's so hard when you want to better for the environment*" (FG8:6). Such predicaments reveal the difficulty associated with consumer decision-making and when it comes to implementing measures for residential decarbonisation.

Following their grievances about their existing boilers, participants in fuel poor dwellings welcomed a "*smaller, quieter, and smarter boiler system that could be better controlled from a phone*" (FG6:2) and ideally, "*voice activated*" (FG6:3). One participant also described underfloor heating as being "*…more space saving and convenient than storage tanks and radiators*" (FG1:1), however, references to this technology were limited to just two focus groups (FG1 and FG5). Synthesising these insights, it follows future boiler systems should optimise for the following features: thermal comfort and ease of use; energy efficiency and smart performance; transparency regarding green credentials; and space savings and noise reduction.

7. Discussion and conclusions

This study addresses a research gap concerning consumer preferences for cooking and heating technologies, with a specific focus on willingness to adopt hydrogen hobs and boilers in the context of socio-technical imaginaries or visions for low-carbon homes. The analysis suggests consumers have distinct perceptions of the prospect of switching from natural gas to hydrogen appliances. Overall, the results suggest no discernible difference between consumer willingness to switch to hydrogen cooking or heating, with moderate levels of willingness and little resistance or opposition. However, when combined into the promise of a hydrogen home, consumers appear generally more supportive of this prospect and see a place for domestic hydrogen in the UK's energy future, with around one-third of respondents proving *very supportive* and close to two-thirds positioned as *somewhat supportive*. Provisionally, it appears that consumer acceptance for the transition may increase if the notion of a hydrogen home entails both cooking and heating technologies. Nevertheless, the stakes for social acceptability, as well as the environment, remain higher with hydrogen boilers.

The findings reveal that some consumer attitudes may prove more static, whereas others are likely to be more dynamic. Dynamic preferences revolve around cost, performance, fashion, and culture [195,196], thus changing with market trends, technological advancements, and culture. For example, the emergence of induction hobs marks an important transition in consumer preferences towards cleaner, sleeker and more modern cooking appliances. Similarly, technology development sees consumers expecting to upgrade to smarter cooking and heating systems when investing in new appliances. Should hydrogen hobs and boilers fail to make significant inroads in these regards, consumer acceptance may still prove feasible, provided hydrogen's environmental and safety credentials are successfully demonstrated and effectively publicised. Nevertheless, cost factors may invariably trump all other concerns for most consumers. Critically, energy costs remain subject to unprecedented unpredictability following the ongoing gas crisis [97] and Russia-Ukraine conflict [197,198,199], alongside government plans to potentially decouple natural gas and electricity prices [200].

The emergent cultural change towards stronger environmental values, embedded across parts of society and within UK households, will shape the transition. Foremost, hydrogen must prove itself as a truly low-carbon solution to compete effectively with alternative technology options such as heat pumps. Over time, the idea of intergenerational justice [201] may also play more of an active role in shaping consumer acceptability towards cooking and heating technologies. At the same time, as the domestic environment becomes increasingly populated with monitoring devices such as smoke alarms and carbon monoxide detectors, hydrogen appliances will need to reinforce a sense of security and control [202]. Safety features are especially critical to households facing fuel poverty, contending with energy vulnerabilities, or otherwise composed of young children or the elderly.

Certain consumer attitudes may instead prove rather static due to conventions deeply entrenched in culture, social norms, or behavioural needs and habits. For example, the preservation of traditional cooking for ethnic foods – reliant on gas cooking – make up a significant part of domestic life and identity for some citizens. In such instances, cooking performance linked to the flame characteristics of gas may outweigh safety or environmental concerns. On the heating side, notions of thermal comfort are entrenched in historical practices and socio-cultural norms, wherein "conditions and concepts of comfort" have been reproduced for decades, albeit with widespread differences across locations and demographics [203]. Consequently, many consumers have deeply rooted practices for thermostat management, which may also vary significantly within the same household [204].

Notwithstanding, as Shove et al. [203] argue "meanings and definitions of comfort are not set in stone." A case in point within this study are participants from Focus Groups 6 and 10, who were selected due to facing conflicts between the choice of *heating or eating* during winter months. In turn, fuel poor households must often rely on secondary solutions and measures, such as extra clothing and blankets, and hot water bottles, [205,206], among other fallback options [95]. Fuel poverty exemplifies the gulf between parts of UK society; underpinned by a heterogenous housing stock populated by a wide range of cooking and heating appliances, which are operated by consumers with varying levels of technical knowhow and environmental awareness. Accordingly, consumer heterogeneity must be internalised into policy making for residential decarbonisation.

In view of the unpredictability of energy transition processes, Davies et al. [207] argue that progress on residential decarbonisation calls for collaboration between multiple specialisations, including "building physicists, engineers, economists, epidemiologists, statisticians, behavioural scientists, complexity scientists, and policy makers," among others. By enriching our understanding of consumer preferences cooking and heating technologies – from the perspective of existing users of gas hobs and boilers – this analysis contributes to the behavioural sciences and policy making. Foremost, the findings can help set a future research agenda for exploring domestic hydrogen acceptance, wherein multi- and inter-disciplinary research teams coalesce to help safeguard public health and safety, community well-being, and the environment [208], in line with the fuel poverty and net-zero agendas [209].

Future studies should also incorporate the use of in-person focus groups to allow for different group dynamics [210], which may result in additional richness and diversity in parts of the data gathering. This may also help counteract one of the tendencies observed in some of the groups, wherein responses from a minority of knowledgeable or extravert participants may have offset further engagement from more tentative participants. In part, this pattern may be attributed to personal comfort with communicating using an online platform (e.g. Zoom). For example, some respondents were cautious to communicate without first raising their hand and receiving acknowledgement form the moderator, despite being reminded to contribute openly. One participant also admitted that it was their first-time using Zoom, while a minority of participants experienced occasional technical difficulties.

In addition to reflecting the nature of group dynamics and individual personalities, the disparity between levels of active participation corresponds more directly to knowledge and awareness levels concerning energy and hydrogen specifically. Typically, participants with some engagement in environmental issues and knowledge of the energy transition assumed the lead during certain parts of the discussion, which is to be somewhat anticipated. Where applicable, follow-up work can take pre-emptive action during the design phase to minimise this pattern. Alongside ensuring a mix of focus group formats, which will allow for potential analysis between in-person and online approaches, other qualitative methods such interviews and deliberate workshops [55,61,211] should continue to enrich the evidence base on domestic hydrogen acceptance.

Researchers should also explore novel approaches which emphasise the use of alternate information provision materials [212], such as exposing different respondents to specific colouring or framing (i.e. positive and negative information) around aspects of the hydrogen transition [62,213]. Our analysis highlighted the role of information provision acutely at times, for example, one respondent felt reassured after seeing the video segments on hydrogen homes:

> *Normally when you think of a new technology, you think everything else is going to be new but the fact that those houses didn't look anything space age; just a normal house with a normal cooker and a heating system, that made me feel a lot more comfortable with it* (R5:2).

This study adds online focus groups to the repertoire of qualitative methods exploring domestic hydrogen acceptance; however, it is admittedly explorative and at best, partially representative of the UK population. Therefore, the results provide inferences, but should not be extrapolated beyond the boundaries of the final recruitment [214]. Moving ahead, the generalisability of results can be enhanced by undertaking large sample survey studies, including additional multigroup analyses and cross-country comparisons. In the UK context, clear opportunities for follow-up work include nationally representative and targeted survey studies, different sampling approaches in terms of socio-structural characteristics, as well as alternative recruitment from specific locations such as the East Coast Cluster or industrial towns in Scotland and Wales, in addition to rural areas of the country. This diversity can help inform different aspects of decision-making, especially around the socio-spatial dynamics of residential decarbonisation and the hydrogen transition. Finally, future studies can adopt an alternative approach to this analysis by conducting polls at the outset of the analysis (pre information provision), and then administering the polls a second time at the end of the study. Such an approach could help provide richer insights regarding changes in consumer attitudes and the role of information provision, while also providing a deeper narrative in respect to group differences.

Developing a comprehensive understanding of socio-technical imaginaries for domestic hydrogen futures is no easy task. However, we contend that tangible progress can be made by adopting a whole-systems approach. It emerges that consumer preferences for domestic cooking and heating technologies should be examined in parallel to the visions and ideas emanating from boiler manufacturers and engineers, housing developers and architects, policy makers, and other key stakeholders across the emerging hydrogen actor-network.

CRediT authorship contribution statement

Joel A. Gordon: Conceptualization, Investigation, Data curation, 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 interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data underlying this study can be accessed through the Cranfield University Online Research Data (CORD) Repository at: https://doi.org/10.17862/cranfield.rd.20727982.v1; https://doi.org/10.17862/cranfield.rd.21081670.v1.

These materials will be released once the results are published (currently under embargo until 01/04/2023).

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Appendix A

Table A1
Breakdown of focus group categories and filtering details.

Focus Group category and sample size	Filtering details
Moderate interest in renewable energy and in joining a renewable energy community ($N = 5$)	• Most respondents answered 'possibly' to being part of a renewable energy community (one respondent answered 'probably') • All respondents expressed a moderate level of knowledge about renewable energy technology • No respondents owned solar PV panels
Strong interest in renewable energy and in joining a renewable energy community ($N = 6$)	• All respondents answered 'absolutely' to being part of a renewable energy community • All respondents expressed high level of knowledge about renewable energy technology • Half of the respondents owned solar PV panels or an electric vehicle
Owners of solar PV panels and smart home technologies ($N = 11$)	• All respondents owned solar PV panels (varying between less than one year and more than five years) • All respondents had at least six smart home technologies[a] • Eight respondents drove an electric or hybrid vehicle

(continued on next page)

Table A1 (*continued*)

Focus Group category and sample size	Filtering details
Actively engaged in environmental issues (*N* = 12)	• All respondents answered affirmatively to valuing the protection of nature and the environment, being concerned about climate change, prioritising government spending on the environment, and encouraging environmental education in schools • In some cases, respondents expressed willingness to vote for the Green Party or another environmental party
Living in industrial cities or towns (*N* = 5)	• All respondents satisfied the inclusion criteria solely based on their location, provided they were users of gas hobs and boilers • Attention was paid to socio-demographic characteristics when filtering the final selection, as a means of preserving a broadly nationally representative survey sample where feasible • This approach encouraged a potential mix of participants, while expediting the recruitment process
Citizens facing fuel poverty or high levels of fuel stress (*N* = 13)	• All respondents faced challenges around eating and heating decisions • Most respondents spent more than 10 % of their income on energy bills and lived in a property with an energy efficiency rating below Band D • Several respondents lived with children below the age of five (*N* = 9), while a few lived with people above the age of 65 (*N* = 3) • In some cases, members of the household also had mobility impairments or special needs (N = 3)
Baseline Group (*N* = 6)	• Uninterested in joining a renewable energy community • Not owning solar PV or multiple smart home technologies • Not actively engaged in environmental issues • Not facing fuel poverty or fuel stress • Living outside of an industrial area

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

Table A2
Overview of information provisional materials.

Information type	Purpose and framing	Description of content
Animated PowerPoint slides	Factual information for newcomers to hydrogen	• Overview of the UK Hydrogen Strategy [11], explaining its links to decarbonisation around the country's largest industrial clusters [215]. • Overview of 2030 and 2035 timelines and energy demand projections for deploying hydrogen across the industry, power, buildings (for heat), and transport sectors [11]. • Overview of 'grey', 'blue', and 'green' hydrogen [216], including a map of blue and green hydrogen projects taken from the Hydrogen Strategy: "Proposed UK electrolytic and CCUS-enabled hydrogen production projects" [11].
Two-minute Channel 5 News segment on the UK Hydrogen Strategy (https://www.youtube.com/watch?v=g-VpyglBhrI)	Media representation of hydrogen giving a sense of different perspectives	• Statement from the Head of hydrogen projects, Northern Gas Networks, Tim Harwood, providing an industry perspective. • Statement from former UK Business and Energy Secretary, Kwasi Kwarteng, providing a government perspective. • Statement for Greenpeace Chief Scientist, Dr. Doug Parr, providing a non-governmental organisation (NGO) perspective.
One-minute video on the H21 Project led by Northern Gas Networks (https://www.youtube.com/watch?v=CtAzCv5Sc48) [55,217]	Bridge the knowledge gap around the use of hydrogen in homes through visual demonstration and written information	• In the UK, 83 % of homes use gas for heating and cooking. • This accounts for around 30 % of our emissions. • The H21 project, led by Northern Gas Networks is demonstrating how our gas network could be converted to carry hydrogen. • This includes trialling hydrogen boilers at three demonstration houses. • The boilers have been developed by Worcester Bosch and Baxi. • They heat homes just like the boilers we use today. • But because they burn hydrogen, they emit no carbon. And could be the least disruptive route to a net-zero carbon future.
Animated PowerPoint slide	Mapping the key actors and stakeholders of the UK hydrogen landscape	• Explaining the supply side related to different energy companies and market competition. • Explaining the role of Gas Distribution Network Operators (GDNOs) in managing the gas grid. • Explaining the role of central government and independent entities such as Ofgem (Office of Gas and Electricity markets). • Explaining the role of trades bodies and boiler manufacturers. • Explaining the role of business, industry, and academia.
Animated PowerPoint slide	Illustrating the spatial dynamics of the UK domestic hydrogen transition	• Outlining the sites of hydrogen trials and demonstration projects. • Outlining the first cities and towns where domestic hydrogen is forecasted. • Underlining the role of and location of hydrogen hubs and industrial clusters.

Source: authors' design.

Table A3
Consumer concerns regarding the costs of over gas heating.

Participant	Illustrative quotations
FG1:2	• *I pay extra insurance to get my boiler serviced every year and in case anything ever goes wrong…so I have that added security, but it does cost quite a bit. The costs are the main problem looking ahead.*
FG3:3	• *The only real downside I see is the cost keeps going up with the energy crisis.*
FG7:4	• *One of the problems with gas is it seems less precise in its measure of energy compared to electricity…with my energy company if I use electricity between 5.30 am and 12.00 am it's a quarter of the price, but no one seems to offer different rates with gas.*
FG8:2	• *Gas has cost me a fortune! I've paid about £4500 to have my boiler replaced in 2012 and about 18 months ago I spent another £800 to get it to work again. That didn't fix the problems such as broken controls or timers. It's set at a certain temperature now whether I like it or not.*
FG8:9	• *I agree that it is quite costly to repair or replace a gas boiler.*

Table A4
Mean score and rank for domestic hydrogen acceptance by focus group category.

Focus Group category	Mean score	Rank	Difference from mean score across focus group categories
Moderate interest in RE and joining a RE community	3.58	4	−0.15
Strong interest in RE and joining a RE community	4.27	1	0.54
Owners of solar PV panels and smart home technologies	3.52	5	−0.21
Actively engaged in environmental issues	3.26	7	−0.47
Living in an industrial city or town	3.93	3	0.20
Living in fuel poverty or facing fuel stress	4.06	2	0.33
Baseline Group	3.50	6	−0.23
Mean score across focus group categories	3.73		
(Standard deviation)	(0.36)		

Table A5
Analysis of relationship between age and domestic hydrogen acceptance by rankings.

Focus Group category	Mean age bracket	Mean score for age[a]	Mean score for hydrogen homes	Age rank (youngest to oldest)	Acceptance rank (highest to lowest)
Moderate interest in RE and joining a RE community (FG1)	36–45	3.60	3.58	4	4
Strong interest in RE and joining a RE community (FG2)	46–54	4.00	4.27	5	1
Owners of solar PV panels and smart home technologies (FG3 and FG9)	26–35	2.80	3.52	2	5
Actively engaged in environmental issues (FG4 and FG8)	36–45	3.30	3.26	3	7
Living in an industrial city or town (FG5)	46–54	4.40	3.93	7	3
Living in fuel poverty or facing fuel stress (FG6 and FG10)	26–35	2.20	4.06	1	2
Baseline Group (none of the previous categories, FG7)	46–54	4.30	3.50	6	6
Mean	36–45	3.51	4.08		
(Standard deviation)		(0.81)	(0.41)		

[a] Point system for calculating mean score for age: 1 = 18-25; 2 = 26-35; 3 = 36-45; 4 = 46-54; 5 = 55-65; 6 = 65+.
Source: authors' calculations.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103204.

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