Received: 25 February 2022 | Revised: 20 January 2023 | Accepted: 20 June 2023

DOI: 10.1002/wene.492

ADVANCED REVIEW

WIREs ENERGY AND ENVIRONMENT WILEY

Public perceptions of heat decarbonization in Great Britain

Sarah Becker[1] | Christina Demski[2] | William Smith[1] | Nick Pidgeon[1]

[1]Cardiff University, Cardiff, UK

[2]University of Bath, Bath, UK

Correspondence
Nick Pidgeon, Cardiff University, Cardiff, UK.
Email: pidgeonn@cardiff.ac.uk

Funding information
UK Energy Research Centre, Grant/Award Number: EP/S029575/1

Edited by: Joseph Nyangon, Associate Editor and John Byrne, Co-Editor-in-Chief

Abstract

Heating contributes significant carbon emissions, especially in countries that rely heavily on natural gas as in the UK. Switching to low-carbon heating is imperative for reaching international climate change targets. Understanding public perceptions and acceptance of low-carbon heating systems is a crucial part of the successful rollout of alternatives. This review examines public perceptions of different low-carbon heating technologies, namely heat pumps, hydrogen boilers, hybrid heating systems, and district heating, as well as social factors such as heat experiences. The review focuses on the UK as a case study, which is characterized by high reliance on natural gas for heating with little progress to decarbonize this sector to date. The next years will be critical regarding decision-making on what low-carbon heating technologies to pursue. The review shows there is generally low awareness amongst the general public of the need to decarbonize heating and of the low-carbon heating alternatives. A number of factors have been identified as playing a crucial role in influencing public perceptions of all low-carbon heating systems, such as installation and running cost, thermal comfort, disruption, level of control, and environmental benefits. However, the acceptance of a new heating system is not simply the sum of several factors, as people's priorities vary across different contexts and technologies. Further public engagement on low-carbon heating and support (e.g., financial) is necessary for increasing uptake. Future research could explore comparisons between the different low-carbon heating technologies, key enabling factors, trade-offs, and concrete policy support.

This article is categorized under:

Climate and Environment > Net Zero Planning and Decarbonization
Policy and Economics > Energy Transitions
Human and Social Dimensions > Social Acceptance

KEYWORDS

district heating, heat decarbonization, heat pumps, hydrogen, public perceptions

1 | INTRODUCTION

Heat decarbonization to achieve climate change targets poses a challenge in many countries that still rely on fossil fuel-based systems. In the UK, heating homes and workplaces contributes to almost one-third of all carbon emissions (Department of Business Energy & Industrial Strategy [BEIS], 2021b). In 2019, the UK government passed legislation committing to achieve net zero emissions by 2050 (UK Government, 2019). The Sixth Carbon Budget (Committee on Climate Change [CCC], 2020) sets out the legal maximum for net territorial greenhouse gas emissions between 2033 and 2037 arising in the UK. These emissions need to be reduced by 78% by 2035 relative to 1990 levels (CCC, 2020), with the heating sector posing some of the greatest challenges (BEIS, 2018). One particular challenge is gas lock-in since approximately 85% of UK households and 65% of non-domestic buildings use natural gas for heating. In 2019 most homes in England were owner-occupied (64%), while 17% were socially rented and 19% were privately rented (Ministry of Housing, Communities, & Local Government, 2020). To reach net zero the heating system in the UK will have to completely shift away from this current majority natural gas-based system. Little progress has been made to date to decarbonize the heating sector. The next few years and decades will be critical for deciding how to facilitate the transition to low-carbon heating alternatives. In addition, and unlike the decarbonization of electricity supply which has started to occur largely without most citizens noticing, changes to the heating system will have to involve users.

Various routes are available for heat decarbonization, including different technologies and demand reduction measures. The three main options currently being considered by the UK government are electrification of the heating system using heat pumps; hydrogen gas; and district heating from low-carbon sources (BEIS, 2020; CCC, 2018). The UK Government's net zero strategy has not yet committed to one technology approach and may employ a combination, with the outcome decided largely by consumer choice (BEIS, 2021b). According to the Energy White Paper (BEIS, 2020): "There is no single technology alternative to fossil fuels. Electric heat pumps and hydrogen, green gas, and shared heat networks all have their part to play" (pp. 109–110).

The current review focuses on the technological options for decarbonizing heat supply and how public perceptions and experiences of these may affect their deployment. There are however other strategies that are important for a successful reduction in carbon emissions of the heat sector including energy efficiency to reduce energy use and demand-side management through smart technologies and smart tariffs—while briefly touched upon in relation to heating technologies, both of these topics are beyond the scope of this review (see e.g., Attari et al., 2010; Brown et al., 2014; Crawley et al., 2021; Gilbertson et al., 2006; Kerr et al., 2018; Ozaki, 2018; Spence et al., 2021). Instead, we focus on how people heat their homes and the associated low-carbon heating technologies, including hydrogen, heat pumps, hybrid heating systems, and heat networks. This technological shift is necessary, and each of these new technologies have implications for the way people use and interact with heating—therefore it is important to understand the available options and public perceptions of them. In this, we assume that in situ heat supply technologies are socio-technical systems (assemblages of technology, people, and governance systems), while also including consideration of people's heating experiences and people's satisfaction with current heating systems.

2 | IMPORTANCE OF PUBLIC ENGAGEMENT WITH HEAT

The transformation of heating will mean significant behavioral shifts for energy users. To date, there has been relatively little research into public perceptions of low-carbon heating technologies, both on individual technologies and in comparison. Given that the public will be heavily involved in heat transformation, for example, as voters and heat users, it is important to understand their expectations and the factors which influence their willingness to shift to a low-carbon heating system.

Understanding public views on changes to the heating system as a whole is crucial (BEIS, 2018; Energy Technologies Institute [ETI], 2015; Furtado, 2019; Judson et al., 2015; Kerr & Winskel, 2022; Wilson et al., 2018). While the UK government acknowledges the role of public participation (e.g., BEIS, 2020, 2021a; CCC, 2020) the current approach relies on voluntary uptake by householders and the assumption that more understanding of the problem and its solutions leads to more acceptability (BEIS, 2021a).

Research suggests there is currently limited public awareness of the significant contribution of heating to carbon emissions, the need for heat decarbonization, and low-carbon heating alternatives, with 50% of the UK public reporting only a little or hardly any knowledge about the need to change (Addario et al., 2020; BEIS, 2022; Furtado, 2019; Sovacool et al., 2021; Williams et al., 2018). For example, when participants were asked about the contribution of different sectors to UK carbon emissions, transport, and manufacturing scored higher than heating and cooling buildings. Notably, waste disposal was perceived to contribute a similar level of emissions as heating and cooling (BEIS, 2021c). In another survey, when asked to pick three actions which they thought would have the most impact on tackling climate change if everyone in the UK implemented these changes, only 29% selected the use of low-carbon heating (Steentjes et al., 2021). A different survey found that questions on the climate change impact of gas central heating were treated more cautiously by participants who otherwise showed moderately high environmental values and awareness (Scott & Powells, 2019). The authors suggest this may reflect people's uncertainty concerning the relative contribution of household heating practices to climate change overall.

Policies designed to address heat decarbonization appear to have relatively high support, however. For example, 62% of a nationally representative UK survey supported the phase-out of the sale of gas boilers (Whitmarsh et al., 2021); a finding replicated in other recent surveys (Demski, Steentjes, & Poortinga, 2022). Nonetheless, it should be noted that this support dropped to much lower levels if this has significant cost implications for householders. This is in line with other research that shows that costs are raised as a particular concern regarding the switch to a new heating system, including the upfront installation and running costs (Chapman et al., 2021). Factors such as the fair distribution of costs of heat decarbonization will need to be addressed, protecting those already in fuel poverty as well as minimizing costs to heat users more generally (Furtado, 2019). The issue of energy costs is becoming increasingly more pertinent with rising gas prices. This is especially the case given the disproportionate amount of income that low-income households already spend on their heating (Milne et al., 2019). However, there are also opportunities to improve people's living conditions and health by reducing damp, draughts, and energy bills (ETI, 2018; Milne et al., 2019).

The low public awareness of heat decarbonization and lack of familiarity with low-carbon heat technologies raises methodological challenges for researching public preferences and acceptance (De Best-Waldhober et al., 2013). This presents issues of information framing in relation to a given risk, technology, or policy (Flynn et al., 2006; Pidgeon, 2020) and how to study public views of the unknown (Ricci et al., 2008), requiring careful consideration of research design. Nonetheless, researching public views at an early stage, while the technology is still emergent, is especially important (Flynn et al., 2009). Currently, district heating systems, hydrogen boilers, and heat pumps are not yet widely deployed in the UK, so the majority of the public has relatively little experience of these to date. Understanding public perceptions at an early stage can be useful to contribute to decision-making on how to include these in heat decarbonization planning at multiple levels such as national-level policy planning and local delivery of heat systems.

2.1 | Aims and methodology

The aim of this article is to provide a succinct review of this UK-specific research on public[1,2] perceptions, and responses to low-carbon heating technologies, to synthesize what we know to date, and identify future research needs.

To identify relevant research, we searched Web of Science and Google Scholar for relevant peer-reviewed publications and supplemented this with a Google search to ensure grey literature is also included (e.g., reports and publications from the government or other relevant organizations). Where available, recent reviews covering specific technologies were included (e.g., Gordon et al., 2022a for hydrogen) to ensure we cover all UK-specific studies.

We only include studies that specifically explore public responses to heat technologies being considered by the UK currently—namely heat pumps, hydrogen gas, and heat networks. We include general perception research which examines people's responses and attitudes to low-carbon heating options, as well as research that examines perceptions of people that have experience of these alternatives, such as participants in hydrogen blending trials, early adopters of heat pumps, or heat network users. Insights from both are important to help make appropriate policy decisions about heating in the future.

We limited our review to the UK context in line with the aims of the study. This enables us to clearly identify where current knowledge stands for our case study, and where important research gaps exists. Other reviews that incorporate insights from international studies on specific heating technologies are referenced where relevant.

The review starts with a brief analysis of public perceptions of existing heating systems and heating practices in the UK. This section aims to set the scene for the later sections on low-carbon heating technologies. This is important context because new technologies are often compared to existing technologies, which are used as familiar benchmarks, for example, in terms of safety and comfort (Flynn et al., 2006; Flynn et al., 2009). The section on current heating systems and practices is followed by sections on heat pumps, hydrogen, hybrid heating systems, and district heating. Each section provides a brief description of the technology, followed by a summary of UK studies on perceptions of these technologies. Where relevant we distinguish between studies that explore general perceptions versus experiences of the technology. The review finishes with conclusions and recommendations for future research and a section on policy implications.

3 | CURRENT HEATING SYSTEMS AND PRACTICES

Research in the UK suggests that there is high satisfaction among the public with gas central heating. Chapman et al.'s (2021) survey found that gas ranked higher than electricity produced from fossil fuels: 50% of respondents indicated that gas is reliable (35% for electricity), 54% find it convenient (42% for electricity), and 56% find it easy to use (43% for electricity). Other survey research also found high satisfaction with existing heating systems, which are often based on fossil fuels (Sovacool et al., 2021).

This is an important consideration for the UK context because of the current high reliance on natural gas for heating. One study found that when participants were spontaneously asked which heating system they would consider using in the future, 90% of those already connected to the gas grid chose a gas boiler (Ipsos Mori & Energy Saving Trust, 2013; also see BEIS, 2018; ETI, 2018). Those off the gas grid mentioned oil boilers most often (40%). The report concludes that people tend to opt for the most up-to-date version of their current system and do not consider alternatives. Further, 70% of homeowners indicated that they would only consider a heating system replacement when their existing one needed significant repair. This indicates that the current appetite for changing to an alternative heating system is low.

Another study (ETI, 2015) found that 90% of research participants prefer gas central heating and less than 4% have low-carbon heating. The research suggested that there might not be obvious benefits to heating experiences by installing low-carbon technologies, especially as many people are reportedly already satisfied with their gas boilers. However, the report notes an example showing that changes to domestic heating systems can be implemented if the alternative offers a better experience. They argue that this was the case when gas central heating first became the dominant heating system—in 1970 only 25% of householders had gas central heating, but this increased to 90% in 2006, despite the cost and disruption of installing these.

Even though people appear satisfied with their gas boilers, many people also indicate experiencing heat-related problems. For example, one report showed that two-thirds of households experience draughts, damp, or condensation and attempt to prevent overheating (ETI, 2018). This suggests that if low-carbon heating experiences could offer improved experiences in terms of thermal comfort, energy efficiency, and health, public interest may increase despite satisfaction with existing gas systems in the UK. This is also evident when taking into account current levels of fuel poverty and people struggling to pay for heating. Heat decarbonization poses an opportunity for a just transition beyond the environmental impact, which could provide immediate benefits and improved wellbeing. Currently, however, high satisfaction levels with existing gas central heating systems, coupled with low awareness of the need to decarbonize heating systems, appears to be a key barrier for uptake of low-carbon heating alternatives.

New low-carbon heating technologies may also require shifts in how people use their heating. While technologies are only one factor which influence heating demand, they are an important element and have the potential to shift practices over time. For example, Kuijer and Watson (2017) drew on archived reports and conducted interviews with residents in Stocksbridge—a medium-sized town in Northern England—to explore why heating demand has increased over time. The authors identify multiple processes to account for this change, including a shift toward separating domestic activities into different rooms (e.g., separating the scullery and living room), increased need for heating due to sedentary and indoor activities, and the introduction of gas central heating replacing a coal-fire in the main living room which meant it was possible to heat more rooms.

Research has also shown that people's expectations of adequate room temperature and thermal comfort more generally have changed over time (Chappells & Shove, 2005; Goodchild et al., 2017), and preferences vary across winter and summer (Sovacool et al., 2021). Computational modeling of changes in UK average indoor temperatures indicates that there has been an increase from 13.7°C in 1970 to 16.9°C in 2008 (Palmer & Cooper, 2012), enabled by relatively affordable gas central heating systems in that time period. Research also highlights that there is more to comfort than reaching a certain temperature and people use their heating to fulfill a number of different needs including, for example, social signaling, personal and pet care, or alleviating pain (Chappells & Shove, 2005; Walker, 2014). As such, heating practices and expectations are not only impacted by technologies and their affordability, but also other social and biographical factors. The Energy Biographies project conducted long-term repeat interviews with households regarding their energy practices and everyday energy use, highlighting how practices around heating comfort are related to social relationships (e.g., taking care of and entertaining family and friends) and can change over the life-course (e.g., Groves et al., 2016; Henwood et al., 2015; Shirani et al., 2017). The warmth of a room also influences how much time people want to spend there and the type of emotional well-being people associate with it (Goodchild et al., 2017).

The extent to which energy use is considered a luxury or a basic need has also changed over time and varies from person to person (Demski et al., 2019; Goodchild et al., 2017). Accordingly, behaviors for managing temperature have adjusted (and still vary depending on income), such as only heating one room in the house or layering up with clothes to keep warm (Goodchild et al., 2017). Some behaviors, such as switching the heating on or off, or boosting heating when heat is needed—as is possible with the rapid response of natural gas boilers—may have to change. Other research has discussed the role of time and social schedules around work and school, which heavily impact on peak electricity demand. This is particularly relevant for the rollout of heat pumps, as demand will need to be spread out to avoid increasing peak loads (Hanmer et al., 2019). Further, heating demand patterns do not perfectly match with occupancy of the home, as people may have the heating off even if at home during the day (Hanmer et al., 2019).

4 | ELECTRIFICATION OF HEATING—HEAT PUMPS

Switching to an electric heating system means replacing the current boilers running on natural gas with heat pumps or with high-performance electric radiators (although the UK government's focus is on the former). There are different types of heat pumps, namely air, water or ground-source heat pumps. They can run off the existing electricity infrastructure and have the potential to be net zero if powered by renewable energy. The UK government currently plans to install at least 600,000 electric heat pumps per year by 2028 (BEIS, 2020, 2021a). There are, however, questions as to whether the funding made available for this plan is sufficient (Boydell, 2021). Additionally, other analyses challenge this target, by suggesting that in fact 900,000 heat pumps per year are needed by 2028 (CCC, 2021).

In contrast to hydrogen (Section 5), the necessary technologies for heat pumps are already available today. Heat pumps also have the advantage that they can, in principle, be reversed to provide cooling, subject to how they are installed. One disadvantage is that they require space for a hot water cylinder and often an external unit. They also run better with underfloor heating or larger radiators and often require radiator upgrades because they run at lower temperatures.

Retrofitting buildings to improve energy efficiency is expected to be a key part of the heat transformation and is widely seen as cost-effective in techno-economic analyses (CCC, 2020). High levels of additional insulation are not critical for the deployment of heat pumps—although it is beneficial from a cost, comfort, and system impact perspective (Lowe & Oreszczyn, 2020). Heat pumps can be scaled to the heat demand of the building.

The key challenge of electrification concerns the capacity of the electricity grid because it would have to provide a significant amount of additional electricity to match the energy currently provided for heating by gas, especially in the winter heating season (Wilson et al., 2018). This challenge is not unique to the heat sector as the electricity grid will need to be reinforced to support decarbonizing other sectors too, for example, to match the demand of electric vehicles (Carter et al., 2017; Lowe & Oreszczyn, 2020).

Expansion of heat pumps in the UK domestic market also faces financial barriers to uptake (BEIS, 2017a). Hanna et al. (2016) reviewed the historical deployment of heat pumps and district heating systems in European countries to learn lessons for the UK. Crucial policies in other countries have included a combination of subsidies, grants, and taxation to help with costs. The research shows that it is especially important to provide support for upfront costs. Further, policy stability is crucial, so that customers, local authorities, and suppliers can rely on consistent support over time. For a review of heat pump cost trends and cost reductions see Heptonstall and Winskel (2021).

Perhaps most relevant for public acceptance, heat pumps may also require a change in heating practices compared to gas boilers. For example, rather than turning up the heating when warmth is required, they need to be run consistently at lower temperatures.

4.1 | Public perceptions of heat pumps

Public awareness of heat pumps tends to be low. A recent survey found that when considering both air and ground source heat pumps together, only 4% responded that they knew a lot about either of them, 20% knew something about one type, and 76% had not heard of or did not know anything about either (Addario et al., 2020). Similarly, research by Williams et al. (2018) found that 42% of survey respondents had never heard of heat pumps.

A recent survey of a representative sample of people in the UK showed 77% supported an ambitious approach to heating, with the government taking an active role (Phillips & Seaford, 2021). The most popular policy choice for heating and electricity was one where the government increases the 2030 target, installing 1.4 m heat pumps in existing homes each year and insulating 770,000 buildings. In this scenario, the government offers grants for some of the additional costs and a government-backed loan scheme that provides low-interest rates, which homeowners can pay back through savings on their energy bills.

Williams et al.'s (2018) research is one of the few studies directly comparing acceptance between heat pumps and hydrogen for heating, concluding that while preferences are not fixed, when participants were forced to indicate a preference, 63% chose heat pumps and 37% chose hydrogen. This was due to the perception that the installation of the hydrogen option is more complicated. Thomas et al. (2022) report deliberative research with existing gas-grid residents in Cardiff, South Wales into their perceptions of potential future low-carbon heating options and potential disruptions to their homes. In-home alterations associated with heat pump retrofit were perceived to be particularly disruptive, while anxieties over operating costs and concerns over interruptions to supply during conversion meant hydrogen did not emerge as an unproblematic alternative either. Demski, Cherry, and Verfuerth (2022) found that participants in their workshops were leaning slightly more toward hydrogen boilers as opposed to heat pumps, with the latter being perceived as more costly and more complicated to install. The authors conclude that public preferences and perceptions of heat pumps and hydrogen are likely still highly malleable and subject to influence by information and discussions with other participants.

These studies also show that people still have many questions and concerns about how heat pumps would work exactly and to what extent they would meet heating needs. Hydrogen boilers were easier for participants to grasp than heat pumps, because they were seen as more similar to natural gas heating systems. Whereas hydrogen boilers were perceived to be a more modern version of natural gas, heat pumps were not necessarily judged as a progressive technology (progressive in the sense of being quieter, faster, and more concealed). In particular, the hot water storage tank and lower responsiveness (in terms of temperature control) were seen as drawbacks for heat pumps.

One of Williams et al.'s (2018) key findings was that participants perceived little benefits from switching to a low-carbon heating system in comparison to natural gas boilers, which is consistent with the research findings on high satisfaction with existing gas central heating systems (Section 3). Participants were also concerned over the additional effort and cost associated with installing and using a new system. The authors suggest that there are significant challenges in communicating about low-carbon heating systems, since participants reported low understanding of alternatives even after receiving information during the research. Similar to Demski, Cherry, and Verfuerth (2022), the authors conclude that low public understanding of heating alternatives means the information materials provided in the study heavily influence the resulting preferences.

Members of the Climate Assembly UK (2020) also showed high support for heat pumps in general (although participants were highly supportive of hydrogen and heat networks as well). Some of the benefits participants emphasized were that they have no emissions at the point of use as they can use renewable energy, they can be used anywhere including rural areas, they are technologically ready and they are considered safe (no flammable gas). Some of the cons discussed were the level of disruption for installation, installation costs, the potential need for insulation, noise, aesthetics, and space requirements. These findings are echoed by a European survey investigating attitudes toward heat pumps installed alongside solar photovoltaic panels (Peñaloza et al., 2022). This study found that economic aspects featured prominently in negative attitudes, whereas perceived reliability and environmental benefits were most prominent in positive attitudes.

4.2 | Perceptions and experiences after heat pump installation

Due to low uptake of low-carbon heating technologies in the UK (Furtado, 2019), there is limited understanding about users' experiences (BEIS, 2018). The existing research indicates that heat pump users mostly have positive experiences and generally good levels of satisfaction (Caird et al., 2012; Energy Saving Trust [EST], 2013; Lowe et al., 2017; Prior, 2019), with some caveats outlined below.

A recent report by the Energy Systems Catapult (2022) investigated motivations and barriers for participating in a project offering free heat pump installations as part of an electrification of heat demonstration trial. The project not only investigated motivations/barriers for joining the project (i.e., interest in participating), but also factors influencing continued participation (i.e., proceeding with the installation of a heat pump). Motivations for joining were most influenced by an interest in sustainability, followed by an interest in new technology, and the promise of a free heat pump installation. Barriers to joining overwhelmingly featured an aversion to the disruption caused by installation. However, notably, this barrier was much less prominent amongst participants who had a pre-existing need to replace their heating system, suggesting that tolerance of disruption is situational. Knowledge and sustainability motivations also had little influence on *continued* participation, despite being the strongest factor influencing interest in participating. The biggest factor influencing continued participation was a pre-existing intention to install a heat pump, with the second biggest factor being a pre-existing need to replace an existing heating system. Data on the use of these heat pumps and user satisfaction is not yet available.

A case study of 21 properties participating in the renewable heat premium payment scheme[3] examined users' experience of heat pumps and the interaction between householders' strategies for operation and level of satisfaction (Lowe et al., 2017). Most users were either satisfied or very satisfied with their heat pump and preferred it to the previous system (18 out of 21). Reasons for high satisfaction varied across households and usually consisted of a combination of factors, such as running costs, the provision of constant heat, and environmental benefits. The research further demonstrated the importance of both technical and social factors in maximizing heat pump performance, with the social factors encompassing issues such as how installers responded to users' requirements and how users decided to control their heat pumps as well as their lifestyle.

The Energy Saving Trust (2013) conducted field trial research with users of ground and air source heat pumps across the UK. Similarly, they found high satisfaction with heat pumps for space heating (80% were satisfied or very satisfied) and for hot water production (84%). Many users (77%) stated they would recommend a heat pump to a friend, primarily due to the running costs and efficiency of the system. Mirroring these findings, an evaluation of the renewable heat incentive[4] found that 83% of owner-occupiers were fairly or very satisfied with their ground source heat pump (BEIS, 2017a; for results on interviews exploring applicants' motivation to install and level of satisfaction see Department of Energy & Climate Change [DECC], 2016).

A survey of 62 homes in the West Midlands installed with a ground source heap pump (Liu et al., 2014) reported a more mixed response, with only 64% of respondents describing themselves as satisfied with their heat pump. Satisfaction was strongly dependent on the quality of information provision and support following installation, with respondents who better understood how to operate and manage their heat pump reporting greater satisfaction and more savings on energy bills compared to their previous system. The quality of the installation itself was also influential, with some respondents experiencing frequent pressure drops and break downs, leading to an increase in running costs and reduced satisfaction. This emphasizes the importance of the installation and instruction process in shaping user attitudes, particularly around information provision and user understanding of the heat pump system, as well as the availability of technical support (BEIS, 2017b; Caird et al., 2012; EST, 2013; Shirani, O'Sullivan, Henwood, et al., 2022; Sweetnam et al., 2019).

Judson et al. (2015) examined 18 householders' experience with newly installed air source heat pumps. Participants' opinion on air source heat pumps was often related to their experiences with the previous, more familiar appliances (see also DECC, 2016). This highlights the importance of measuring satisfaction in comparison to previous heating systems. Their judgment of the new system depended on the extent to which they experienced improved thermal comfort, control, and on the level of active participation required to optimize the heating. The process of installation and instruction was again found to be crucial, as users needed familiarizing with how to operate and optimize the new system. Some participants were concerned that leaving the system running all day or night would add costs. However, this tends to be the most efficient use of heat pumps (see also Sweetnam et al., 2019), depending on the building's efficiency and the electricity tariff. The constant running of heat pumps contrasts with the common use of gas heating which is often programmed to heat homes at specific times or on demand.

Heat pumps installed alongside other low-carbon technologies or innovations such as solar panels or demand-side management (DSM) has not been explored extensively in the UK context. One exception is a qualitative study, which examined social housing tenants' experiences of having heat pumps installed as part of a demand-side response trial in Greater Manchester (Calver et al., 2022). Similar to previous studies, the authors found that the majority of interviewees were positive about the new heat pump system, reporting similar or better thermal comfort levels (e.g., constant temperature/heating), less use of secondary heating, and reliance on other coping mechanisms to keep warm as well as slightly reduced energy bills. Some issues emerged around disruptive installation (especially with dependents at home) and understanding how to control and set up the system to maximize personalized thermal comfort levels. The authors conclude that households were most likely to benefit from the heat pump system if they had a basic understanding of how the system worked (e.g., gradual temperature changes, lower radiator temperatures); homes were not previously underheated; homes had a high daytime occupancy; the desired temperature was set at installation; and the system was left to maintain a constant temperature. In this case study, the heat pump was controlled by an external company to maximize efficiency and reduce electricity load at peak times, which meant that tenants' control of the heating system was more difficult and required communication with installers and controllers during the trial and required usage of bespoke technologies (e.g., an app). This limited some householders in their ability to meet their thermal needs especially when generalized advice did not apply to their circumstances and confidence in using technology was low. This may result in underheating during the day and overheating at night, highlighting the difficulty of balancing load shifting with comfort and users' needs (Sweetnam et al., 2019).

Research for the Living Well in Low Carbon Homes (LWLCH) project further underpins the importance of supporting users with new heating technologies. This project involved longitudinal qualitative interviews with developers as well as residents moving into, and learning to live with, novel "Active Homes" (Shirani, O'Sullivan, Hale, et al., 2022; Shirani, O'Sullivan, Henwood, et al., 2022). Such homes incorporate electricity generation with other demonstration low-carbon technologies (O'Sullivan et al., 2022), including heat pump installation and active demand side management. Active homes, for which there are a number of demonstrator trials currently underway in the UK, may become more common in the future. The LWLCH study highlighted considerable enthusiasm for the active home concept amongst many of the residents, particularly where the system-design as a whole functioned well to provide comfort and affordable energy bills, but also mismatches between certain prior assumptions made by the home designers about occupant behaviors (e.g., regarding ways of drying clothes in the home) and the lived practices and expectations of residents. The research also highlighted the critical importance of close developer-resident relationships, technical support, and information provision regarding the operation of the new technologies, particularly during the first phases of occupancy.

5 | HYDROGEN HEATING

Hydrogen can be produced from water through electrolysis (referred to as green hydrogen) or from natural gas (referred to as blue hydrogen). For blue hydrogen to be considered low-carbon, it must be employed together with carbon capture and storage (CCS) technology. A UK Government report (BEIS, 2018) states that hydrogen could be a feasible development, but there are some substantial caveats. These include, for example, unclear emission reduction potential, feasibility of safe gas grid conversion, new infrastructure for transmission, production and storage of hydrogen, sufficient CCS, and secure sourcing of natural gas for increased demand. The more recent Energy White Paper (BEIS, 2020) similarly acknowledges these challenges: "... unlike electric heat pumps and heat networks, the feasibility of using hydrogen for clean heat needs further testing and development. The practicalities and cost of safely converting or replacing existing networks and appliances to operate with pure hydrogen need to be fully evaluated" (p. 112). Evaluation under the Hy4Heat program, for example, has developed the safety case for hydrogen to replace natural gas for domestic heating and cooking (Hy4Heat, 2020). Specifically, the program examined whether it is technically possible, safe, and convenient to use hydrogen in residential buildings instead of natural gas.

A report by the Committee on Climate Change (CCC, 2018) explores hydrogen as a valuable complement to electrification. For example, hydrogen could replace natural gas for heating buildings on particularly cold days, for industrial processes, and back-up energy generation. According to the CCC, it could enable the UK to reduce emissions by 2050 to a larger extent than would be possible without it. While the report states that hydrogen could contribute to the decarbonization of energy at a lower cost than previously anticipated, it also notes that having an extensive gas grid does not necessarily mean conversion to hydrogen will be cheaper than other options. The analysis suggests that the costs of different heat decarbonization pathways are similar, including ones where the gas grid plays a reduced part or is decommissioned.

Research has pointed toward the significant role of incumbents in over-selling the potential for decarbonized gas to policy makers to protect their own interests and downplay the importance of electrification (Lowes et al., 2020, p. 1). There is evidence of lobbying by gas network owners and appliance manufacturers to maintain a heating system based on gas by switching to hydrogen (Lowes & Woodman, 2018). Due to these incumbents' power, it is difficult for smaller technologies or alternative proposals to establish themselves in the policy discourse. According to the authors, hydrogen has rapidly entered the policy landscape, despite associated uncertainties, such as the costs of adapting the gas network, the technical feasibility of converting the gas grid, and the level of carbon emission reductions. Further, research informing the CCC's sixth carbon budget balanced pathway did not include any standalone hydrogen, the only inclusion of hydrogen was through hybrid heating systems (Element Energy, 2021; also see Section 6).

Currently, only a very small percentage (0.1%) of hydrogen can be injected into the UK gas network based on the Gas Safety Regulations 1996, with some exceptions for testing allowing up to 20% (Majumder-Russell et al., 2021). Nonetheless, partial injection only achieves a small reduction in greenhouse gas emissions, due to the lower energy density of hydrogen (e.g., for an injection of 20 vol.% of hydrogen there is a 7% reduction of greenhouse gas emissions from the final gas blend [Quarton & Samsatli, 2020]). One hundred percent hydrogen deployment would necessitate exchanging gas pipe infrastructure, as well as potentially the gas pipes and boilers within buildings.

Hydrogen's benefits include that it can be used for multiple applications, such as heating, energy storage at scale, industrial use, and for powering heavy transport, in particular trains, goods vehicles, and possibly ships, alongside use in cars. But substantial issues remain around the scale, environmental benefits, and the efficiency of producing hydrogen. Blue hydrogen requires CCS, which does not yet exist at scale, with estimates of the necessary capacity potentially presenting a serious barrier for the feasibility of storage at scale (Hansson et al., 2022). Further, relying on natural gas would also mean continued import dependence and could result in carbon leakage during extraction and transportation. By contrast, using renewable electricity to produce green hydrogen is far less efficient than using the renewable electricity directly to power heat pumps, as "the energy generation costs for heat pumps are 1/6 of those for Green Hydrogen" (Cebon, 2020).

5.1 | Public perceptions of hydrogen for heating

There is relatively little research on public perceptions of hydrogen use (Edwards et al., 2021; Flynn et al., 2009; Hanusch & Schad, 2021), especially with a focus on use for heating, reflecting the fact that the technology is not yet commercially available. Nonetheless, in recent years several publications have reviewed existing research on hydrogen acceptance and proposed theoretical frameworks to guide future social research. For example, Scovell (2022) summarizes the psychological factors that may influence hydrogen acceptance. Scott and Powells (2020), in contrast, propose social practice theory, energy justice, and place attachment as important lenses through which hydrogen perceptions are to be studied. Perhaps the most comprehensive framework is proposed by Gordon et al. (2022b) who, based on a review of the scholarship on social acceptance of renewable energy technologies, propose a framework for understanding acceptance of hydrogen use in domestic settings. Their comprehensive framework consists of five dimensions including attitudinal, behavioral, community, socio-political, and market acceptance. Using this framework, they go on to suggest potential socio-technical barriers to domestic hydrogen acceptance in the UK. Some of the major barriers they predict include financial cost, low knowledge and awareness, disruption during the switchover, concerns about distributional injustices such as geographic inequalities and impacts on low-income households, limited current consumer engagement with energy generally, safety concerns around hydrogen storage and combustion, preferences for green rather than blue hydrogen, limited public trust, and procedural concerns around transparency and fairness in decision-making about the switchover. Rather than seeking to replicate the above reviews, we present a narrative account of the UK studies that speak to understanding perceptions of hydrogen use for heating.

To start, public awareness and knowledge of hydrogen for heat appears low, and indeed lower than other low-carbon heating technologies (i.e., heat pumps), with 50% of the UK public having never heard of hydrogen boilers, and 40% having a little or hardly any knowledge (BEIS, 2022; see also Williams et al., 2018). Another study found that most people did not know that hydrogen burns with a near-invisible flame unlike gas, although this may be more relevant for cooking rather than heating practices (Scott & Powells, 2019).

One of the most recent findings on perceptions of hydrogen in the UK comes from the Climate Assembly UK (2020) where members discussed various pros and cons of hydrogen for heating. Some of the pros included that it was seen to work with the current infrastructure, easy to transition (both for gas companies and in terms of consumer familiarity), widespread use may reduce cost, emission reductions, and it is good at keeping the house warm. One member stated: "I have gas already and I know it works. Green hydrogen would be the ideal solution in an ideal world" (p. 178). Some of the perceived cons discussed were that the technology is not ready (especially at scale), it is expensive, the use of carbon capture and storage was a concern (with a preference for green hydrogen) and safety risks. In their research on converting the gas network to hydrogen, Fylan et al. (2020) found similar public responses. People expressed concerns about the use of hydrogen and its production, cost, safety, questions about the timing and practicalities of the switchover, and how it would compare to gas central heating systems in terms of operation and meeting heating needs.

As mentioned in Section 3, Williams et al. (2018) and Demski, Cherry, and Verfuerth (2022) found contradictory preferences in their samples on whether hydrogen was preferred over heat pumps, with the option that is perceived to be the least hassle to install being preferred. The unfamiliarity of hydrogen as a heating option, therefore, makes public perceptions relatively susceptible to information provision. This is underpinned by a number of other studies on the use of hydrogen. For example, Bögel et al. (2018) conducted a survey including the provision of information across seven European countries to explore public perceptions of hydrogen technologies, focusing on hydrogen fuel cell electric vehicles and home fuel cells for heating and electricity. The results show low awareness of hydrogen technologies and low attitude stability. The authors compare a measure of general attitudes toward hydrogen technologies (measured before information provision) to attitudes to a specific fuel cell application (measured after information provision) and find that the latter is more positive than the former. This suggests that either attitudes toward a more specific application are generally more favorable or that the information provision concerning a specific application led to a significant improvement in attitudes. The authors propose that it is useful to implement information campaigns at an early stage of new technologies before attitudes are formed which may bias the processing of information.

While both heat pumps and hydrogen options tend to be evaluated along similar criteria (e.g., cost, installation hassle, ability to provide thermal comfort, and control), there are some aspects that are more salient in public responses to hydrogen specifically. These include safety concerns and questions about the production and source of hydrogen. These are now briefly discussed in turn.

In terms of safety, Cherryman et al. (2008) conducted two focus groups in Wales to examine perceptions of hydrogen production and end use of hydrogen energy. They found participants generally had supportive attitudes overall and their main concerns were over the costs and safety. This is in line with other research, for example, Ricci et al. (2006) propose that public acceptance of hydrogen is likely to vary depending on the specifics of each application and emphasize the importance of transparent communication about hydrogen-related safety risks for each context. Sherry-Brennan et al. (2010) conducted a survey of households in Unst, one of the Shetland Islands. Unst has a renewable wind-hydrogen generation and storage system that was completed in 2005, which is community owned. In their research drawing on free associations with hydrogen, the authors found that despite awareness of associated risks (explosion and flammability) there were nonetheless positive evaluations in response to being prompted on "hydrogen" and the project, which outweighed the negative risk perception. More recent research supports these initial findings. It suggests that hydrogen is still associated with explosions and accidents, and as such safety risks are important considerations for people. Nonetheless, UK participants across multiple studies appear relatively confident that adequate safety measures will be put in place prior to hydrogen being used at scale (Scott & Powells, 2019).

Several studies have also found that the source of hydrogen is important in determining public perceptions, with a preference for hydrogen from renewable energy over hydrogen produced from gas. This is also evident from international studies (e.g., Ashworth et al., 2019; Finkel et al., 2018) and those on transport use (Bellaby et al., 2016). The idea of continuing to use fossil fuels to produce low-carbon heat is something participants question as illogical and not representing sustainability or progress—in effect being a "non-transition' (Butler et al., 2015). This is also underpinned by research on the use of carbon capture and storage, which would be necessary for blue hydrogen. Compared to the literature on public perceptions of hydrogen, the research on CCS is more extensive (see e.g., L'Orange Seigo et al., 2014; Thomas et al., 2018). In the context of fossil fuel-based energy production, CCS is often perceived as an unnatural procedure that is associated with risks, such as seismic activity, and is therefore dependent on good long-term safety management. These initial assessments have been found to give way to more sympathetic responses when CCS is contextualized within renewable energy intermittency. This was especially the case if participants were not in favor of demand-side responses to intermittency, such as time-of-use tariffs. Other factors that have emerged to be important for CCS are trust and its past and present role in creating employment (Thomas et al., 2018).

5.2 | Public perceptions of hydrogen trials

The feasibility of using hydrogen for heating is still being tested and as such there are no publications on householders' experience of using hydrogen boilers. A group of gas distribution network operators in the UK are however undertaking trials to test the proposition of using blended (hydrogen blended into the existing gas network) and the potential use of 100% hydrogen for heating (see Gordon et al., 2022a for a summary of past and current trials). In future years, it is expected that the next trial phase will involve the actual conversion of communities and homes, but currently, no published data exists on people's experiences in these trials. There are however two publications that have explored perceptions of hypothetical trials and those living in trial regions, which we briefly cover here.

Gray et al. (2019) conducted focus groups with potential participants in a community hydrogen trial to explore possible reasons for and against participating. The described trial was modeled on the H100 Fife project, which is the first community trial of green hydrogen, and involved an opt-in process of about 300 homes in Levenmouth, Scotland. The findings show that householders' motivations varied and that both environmental reasons more generally, and specific individual benefits can motivate people to take part. In line with other findings around installation, people are willing to tolerate some disruption as long as they know they will not be worse off afterward both financially and in terms of thermal comfort. Justice concerns also emerged as important, for example, people expressed concerns for vulnerable groups and how they would be looked after. Clear communication and transparency are important for building trust, particularly due to the unfamiliarity and uncertainty inherent in these trials. Echoing general perception research on hydrogen, people were not overly concerned about safety, although given it was a trial some reassurances were sought about this aspect. Information provision and post-installation support were considered critical, with tailored information to meet householders' specific needs and circumstances as ideal. Findings were mixed in terms of financial incentives for the community and individuals to take part in the trial with both positive and negative reactions.

Scott and Powells (2020) set out to understand perceptions of householders broadly representative of two communities in the north of England where the second phase of the HyDeploy project was based. This trial involved the injection of small quantities of hydrogen into the current gas network (Scott & Powells, 2019). Findings from a representative survey showed that the perceived cost was the most significant concern raised, with 77% of respondents indicating they would be unwilling or unable to pay more than they currently spend on energy; a concern which we suspect has only increased in the current cost-of-living and energy price crisis. Safety concerns were also important, with 44% of participants stating they were very or quite worried about potential gas leaks, fires, and explosions. Further, participants' initial concerns regarding safety were significantly associated with their overall support for hydrogen. However, these concerns appear addressable as 77% stated they were confident that adequate safety measures would be implemented. Initial awareness of hydrogen blending was low and there was no strong sense of rejection or acceptance, which the authors describe as a blank slate for hydrogen acceptance. As part of the survey participants received information about hydrogen blending in the UK context (that home appliances in the UK have been tested to operate safely with 20% blended hydrogen and regarding the previous common use of town gas composed of up to 50% hydrogen in the UK). After receiving this information, participants were more willing to use hydrogen and perceived there to be environmental benefits without detrimental impacts on their household appliance usage. The authors recommend that building trusted channels of communication with the public about hydrogen blending is crucial. Participants indicated low trust in the media and local MPs, while the Health and Safety Executive (the longstanding UK workplace safety regulator) and scientific evidence were seen as more trustworthy. Especially important is the upstream engagement of the public in decisions (see also e.g., Pidgeon, 2020; Rogers-Hayden & Pidgeon, 2007) and not passing on costs to consumers, with the authors suggesting this could jeopardize acceptance. They conclude that while environmental initiatives such as hydrogen blending are valued, limited budgets mean that people are largely unable or unwilling to pay more for hydrogen blending.

6 | HYBRID HEATING SYSTEMS: HEAT PUMPS WITH GAS/HYDROGEN BOILERS

Hybrid heating systems are a combination of two heating systems. The heat pump is expected to provide the majority of the heat and the gas or (future) hydrogen boiler provides back-up during extreme cold events when electricity is very expensive or when the heat pump is struggling to produce enough heat. The benefits of the hybrid heating systems are that the boiler can produce a higher output at lower external temperatures, while the heat pump can provide consistent low-temperature heating with less energy and cost (The Carbon Trust & Rawlings Support Services, 2016). Such systems can also respond to market signals, that is, electricity market prices choosing which heating system is cheapest/lowest carbon. A smart hybrid heat pump system can switch between the two sources to optimize costs and energy efficiency. Hybrid (often referred to as bivalent) systems are already commercially available and in 2016 made up 18% of the market share of heat pumps (The Carbon Trust & Rawlings Support Services, 2016).

6.1 | Public perceptions and experiences of hybrid heating systems

There is currently little research into public perceptions of hybrid heating systems. The Freedom Project is an initiative between Western Power Distribution and Wales & West Utilities to test hybrid heating in Bridgend, South Wales. In 75 properties, an air source heat pump and high-efficiency gas boiler hybrid system were tested (Freedom Project, 2018). The report suggests that hybrid systems may offer low-cost solutions because they can avoid the need for costly and disruptive retrofitting of buildings and avoid capacity peaks on the electricity system. A key aspect of this approach is a smart control system to manage flexible demand, with the authors claiming that: "The future cost of delivering power will be determined by how and when customers consume, not how much they consume." The focus is thus on changing customers' time of use of energy, rather than reducing energy consumption. Public perception of demand flexibility is therefore important to understand in this context.

User responses of the hybrid heating system were largely positive, with some caveats. Some users struggled with not having direct control over their heating system because instead they had to input their desired comfort levels in the heating control system. As also shown in some of the heat pump trials mentioned above, there was sometimes a lack of understanding why the heat pump was running outside expected times. Some participants perceived there to be a higher use of electricity than was actually the case and the authors emphasize the importance of householders being able to see that they are making savings. The authors also recommend introducing different levels of control and information, as users vary in the extent to which they want to engage with a heating system, echoing research from both hydrogen and heat pump trials which has found that information provision needs to be tailored to individual needs.

7 | DISTRICT HEATING

District heating, also referred to as heat networks, involves a heating system where heat production is centralized and then transferred to a network of buildings through insulated pipes. The heat can be produced from a variety of sources, including non-renewable sources (e.g., natural gas) or renewable sources (e.g., renewable-powered heat pumps). Currently, heat networks provide only around 2% of space and water heating in the UK (Association for Decentralised Energy, 2018). Although global averages for district heating use are low, it covers a high share of heat used in buildings in some countries, including Denmark and Sweden (over 45%), China (approximately 15%), and Russia (approximately 45%) (International Energy Agency, 2021).

7.1 | Public perceptions of district heating

There is very little research examining public perceptions of district heating in the UK. Unlike for heat pump and hydrogen options, there is very little research on the awareness and knowledge of heat networks. One exception is a local survey conducted in Neath Port Talbot which showed that only 9% of respondents had heard of district heating. After brief information about district heating, 87% agreed that it sounds like a good idea in principle, while 87% also wanted more information and 56% agreed that they were not quite sure what district heating involved (Upham & Jones, 2012).

When presented with different pros and cons of district heating, members at the Climate Assembly UK (2020) placed importance on the fact that district heating can be cheaper for households, efficient and effective, that it involves a mass change, that the technology is already in use and that it may create a sense of community. The downsides were perceived to be that it is not suitable everywhere, it may be disruptive to install, there is loss of individual control (everyone has to opt in), and it may be expensive to implement.

Shirani et al. (2020) report 4 waves of qualitative longitudinal interviews with residents of Caerau, a former mining community in the South Wales Valleys with many low-income households and significant local health inequalities. Proposals had been made by the local Council, and geotechnical investigations undertaken, to site a demonstrator district heating scheme for homes in the community, based upon exploiting energy from mine-water in the abandoned coal workings below the village. Although the scheme did not subsequently go ahead, virtually everyone interviewed saw one of its main benefits as using a resource that was otherwise lying idle, and which had a strong association with the community's mining heritage. However, interviewees felt that it would need to result in a reduction of household energy costs to convince people to join, and what was considered to be a sufficient saving varied between households and according to expected disruption. Some who recalled unsuccessful district heating schemes elsewhere, or who had experience of poorly executed energy efficiency schemes in the past (such as for external insulation), were wary of signing up to any new heating scheme, while residents also wanted clear information about how repairs and system maintenance would be dealt with. Beyond short-term advantages to individual householders, study participants were also keen that the proposed scheme could demonstrate benefits to future generations locally.

Upham and Jones (2012) examined public responses to the use of waste process heat for district heating by conducting two focus groups in Newcastle and a survey of residents in Neath Port Talbot, near the former Corus (now Tata) steel works. The majority of focus group participants had gas central heating and had not made changes to their heating system. The authors suggest that any changes toward district heating, therefore, need to be as good as the existing heating system and require minimal changes to routines. This is in line with findings from hydrogen and heat pump research. When asked to identify the characteristics of heating systems that were most important to participants, they mentioned cost, reliability, comfort, simplicity, convenience, efficiency, and environmental factors (however, the environment was a low-level consideration).

Focus group participants were largely favorable toward the use of process heat for district heating. However, there were clear conditions that were placed on this support. Participants required it to meet the same standard of provision as current heating and hot water systems, maintain a similar or lower cost, and hold environmental benefits. Participants inquired about the reliability and potential leakages of district heating. There was also the sentiment that it would have to be successfully tried and tested before some participants would be willing to go through the upheaval of changing to a new heating system. Another important factor was the controllability of the water and heating temperature (see also Hodges et al., 2018). Finally, there were concerns about cost and specifically about the potential to be locked into district heating and susceptible to rising prices (see also Hodges et al., 2018; Zaunbrecher et al., 2016). Concerns about lock-in were adjacent to sceptical beliefs about the ongoing success of local industry responsible for providing heat, especially in times of growing economic uncertainty. This raised discussions around ownership, contracts, and financial reliability, highlighting the importance of confidence and trust in the supplier, which are particularly dominant for this type of heat provision.

The study also included a survey to examine participants' willingness to accept being tied into a contract for either 1 or 2 years, as well as some installation disruption, in return for a 10%–20% reduction in heating bills per year. In this context, 57% of participants viewed street disruption for pipe laying as favorable and 66% were also favorable toward the installation of a heat exchanger in their home. However, contract tie in posed more concerns for participants. A 12-month contract commitment was viewed as unfavorable by 32% of participants, which rose to 59% for a 24-month contract. When asked to consider which factors were important in district heating, 87% indicated the reputation of the supplier, 95% indicated contract flexibility, 97% indicated cost, 94% chose level of control over the heat supply, 97% indicated reliability, 86% indicated environmental impact. It is worth noting that participants' views varied considerably toward different sources of heat for district heating, with waste heat from industries being considered the most favorable. Biomass was relatively unfamiliar to the sample, as 15% indicated they did not know and 31% were neutral. More recent deliberative research also in the town of Port Talbot, using community workshops to investigate attitudes to local energy system decarbonization (Pidgeon et al., 2022; Thomas et al., 2022), indicates that these concerns about district heating are persistent within the community, and that concerns about decarbonization also reflected nuanced beliefs about both local identity and fairness. Some participants viewed the reliance on process heat from industry as being at odds with the need for the local community to move away from an industrial past. Participants also expressed concern that the necessary logistical limitations to heat network coverage would introduce or exacerbate inequality between those neighborhoods inside and outside of network coverage.

7.2 | Experiences of district heating in the UK

Because heat networks are not very widespread in the UK currently, there is a parallel lack of research into experiences of users of such heat networks. Research for the government examined claims that satisfaction levels among heat network users is similar to satisfaction levels of other heating systems (Fu & Abbassian, 2018; Hodges et al., 2018; Thornton et al., 2017). Satisfaction was higher when the system was perceived as reliable and fairly priced (which was also linked to affordability), users were able to effectively control the heating and hot water output, and complaints and repairs were dealt with quickly and effectively. The research also found that heat network users appear to have less control over their heating system (compared to gas heating), which led to higher reported rates of overheating and more wasteful cooling behaviors (e.g., opening windows). This may also be linked to the finding that a majority of the surveyed users did not pay for usage but paid a set price for hot water/heating. These findings mirror a local survey in London (Greater London Authority, 2018), which found high satisfaction levels (82%) among heat network users. Eighty-four percent report being satisfied with the reliability of the system, seventy-eight percent are satisfied with the information they have received about the system. A majority (77%) also report being satisfied with the level of control over the temperature of their heating, but only about half actually had full control over the timing and temperature of the heating. Those who had less control were more likely to experience over- or underheating.

8 | CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Research on public perceptions of low-carbon heating options in the UK is at an early stage, especially when compared to other sectors such as transport. Public awareness and knowledge appear low across all three options reviewed in this article, even for the established technologies such as heat pumps and district heating. This low awareness coupled with high satisfaction levels for existing gas central heating presents a clear challenge for public engagement as the low-carbon transition evolves.

Given the limited nature of knowledge to date, definitive conclusions cannot be drawn about public preferences and acceptance of the different low-carbon heating technologies currently under consideration in the UK. However, this early research provides an indication of initial responses, reactions, and experiences with them. Across heat pumps, hydrogen, and district heating we find that there are common aspects which are important for influencing how people respond to the idea of changing their heating system. These include installation and running costs, installation burden and disruption, ability to meet thermal comfort needs, level of control, ease of use, safety, and justice concerns. Environmental concerns also feature but perhaps not as prominently as some of the other issues, although this also depends on the information presented and questions asked.

There are aspects that emerged as particularly salient for each technological option. For example, while heat pumps are perceived as safe and technologically ready, concerns around aesthetics, noise, and space appear more prominent than for other technologies. The need to have the heating on a low constant temperature also presents a very different experience of "comfort" to current gas central heating operation. For hydrogen, safety and reliability were still an issue to be resolved due to the unproven nature of the technology, with the source of hydrogen another aspect that may be important in influencing perceptions. Trust in operators appears particularly important in the context of district heating, with issues about contract lock-in potentially problematic.

While clearly, many factors are important in influencing support and uptake of new heating systems, it would be interesting to explore whether there are any key enabling factors, for example, if there was a government-led rollout of new heating systems nationally or locally. If the installation of low-carbon heating systems was paid for and running costs remained similar, to what extent would the other factors (such as disruption of the installation) still matter? This points toward the importance of examining trade-offs and interactions between different factors. One government-commissioned research study did attempt to examine trade-offs of this kind (Addario et al., 2020) and found that climate change concern had a significantly larger effect on acceptance than differences in the heating scenarios presented. Interestingly, variation in the scenarios in terms of level of disruption, household control over the timing of the switchover, and national versus local planning, had a small effect on acceptability. It is possible that the scenarios were still too hypothetical to be meaningful and thus future research would benefit from presenting more tailored information, or through in situ demonstrator studies with residents (e.g., studies on hydrogen trials).

A key finding of this research was that participants perceived little benefits of switching to a low-carbon heating system in comparison to natural gas boilers and were concerned over the additional effort and cost associated with installing and using a new system. Therefore, it is important to consider how low-carbon heating systems can offer benefits and how to make these apparent when engaging with prospective users. The review suggests a role for education and information provision more generally. While environmental concerns are likely to be important motivators for some people, many also want reassurance that their heating needs continue to be met. Indeed, some existing users of heat pumps were experiencing improved thermal comfort and lower bills, and future research could therefore examine how best to maximize these co-benefits and the ways that they shape public perceptions and willingness to change heating systems in the future.

There is also need for more theoretically informed research. Many of the studies exploring experiences with heat pumps focused on a limited number of factors such as satisfaction and people's understanding of the system, rather than, for example, potential long-term savings from running costs. The review does note, however, that several theoretical frameworks for understanding acceptance of hydrogen have recently been published (e.g., Gordon et al., 2022a). This could form the basis for more theoretically grounded research in the future.

This highlights another limitation of the existing research landscape: there were very few studies that included more than one technological option, and there was little learning across technologies despite issues around installation, cost, or information provision being common across these. In addition, those studies that did include multiple technologies found that preferences and perceptions can vary depending on elicitation methods, what information is included, and the framing of information. This is not surprising given the unfamiliar nature of these technologies in the UK. The psychological literature on preference construction (Lichtenstein & Slovic, 2006), and its application to novel decarbonization technology options (Shrum et al., 2020), suggests that people will often use information carefully to come to a considered response. While it is easy to dismiss public preferences as fickle and changeable, these early studies provide an interesting window into how the general public is likely to respond as they learn about the need to decarbonize and the different options that are being considered.

The review included a few studies where new heating technologies were considered alongside other innovations and technologies such as solar panels or demand-side management. The interplay between these and how they affect people's perceptions of technologies is an important area for further study. For example, while heat pumps may provide constant heat and improved thermal comfort, these may be limited if people are not able to control their own heating systems due to the demands placed by external control.

Finally, the research reviewed in this article is still in its infancy and as such is unlikely to represent the wide variety of perspectives and experiences of the UK population and its diverse make up. For example, existing research on heat pump experiences tends to be with early adopters, hydrogen trials are focused predominantly on the north of England and Scotland, and the research on heat networks seems almost exclusively limited to the Port Talbot area in Wales. As such, future research would do well to diversify research samples and locations to capture a more diverse range of perspectives on heat decarbonization.

Further, it is worth distinguishing between the different levels of engagement people have with heat transformation, for example, as heat users, citizens (and dissidents), voters, and different contexts such as domestic, workplace, or policy (Chilvers et al., 2021). For example, it may be easier to connect workplaces to district heating systems than domestic properties since individual buy-in from users would not be required in a workplace.

There are challenges for different research methods in terms of engaging people's imagination. For example, people sometimes found it difficult to envisage the alternatives presented and felt like they still lacked knowledge to form an opinion even after receiving information. Deliberative research that helps to overcome such gaps of knowledge and works with eliciting imagination of future alternatives (both in terms of technologies and ways of living) is required (e.g., Pidgeon et al., 2014, 2022). Another example highlighted in many studies is that it is typically not possible to provide reliable estimates for future heating costs from a new technology deployment, and yet study participants often ask for this in order to make their judgments. Various quantitative and qualitative research methods will also have their respective strengths and weaknesses for tapping into the different facets of public perceptions toward yet largely unknown technologies and changes in practices. This also speaks to the relevance of different research on more general perceptions (prior any specific changes), as well as an examination of views prior and post installation of a new heating system, practice, or policy (e.g., Shirani, O'Sullivan, Hale, et al., 2022; Shirani, O'Sullivan, Henwood, et al., 2022). Research could also look at how attitudes are formed initially and how they change as the technology becomes more concrete and well-known.

As heat decarbonization takes shape in the UK, new issues will also emerge as important. For example, previous research has highlighted the importance of trust in government and energy companies in energy transitions (Becker et al., 2019). Future research could examine the role of trust in different actors, as well as key messengers for recommending and installing low-carbon heating. There is little research on the decision-making process when people choose a new heating system and who they trust for advice and recommendations on this, which merits further examination. It is also important to develop understandings of how public perceptions of heating are formed and shaped on a societal level, such as by media narratives, discourses circulated by policy actors or by prominent social movements, as well as what people are already used to, rather than understanding perceptions as fixed, inherent psychological constructs (Pidgeon et al., 2003; also R. Lowes, personal communication, 2019). For example, gas industry campaigns aimed at influencing public perceptions in favor of gas for cooking (Leber, 2021), with the objective of constructing support for future hydrogen systems may also prove important influences on preference formation.

9 | POLICY IMPLICATIONS

As outlined in the introduction, the current UK Government is relying heavily on "consumer choice" for switching to low-carbon heating (BEIS, 2021b). This is a framing which implies a narrow conceptualization of "the public" with implications for how the role and agency of citizens is viewed in transformation discourses (Lennon et al., 2019). This strategy may prove to be precarious, not least because public attitudes toward low-carbon heating technologies are currently characterized by a general lack of awareness and knowledge (BEIS, 2022). Furthermore, the time pressure for decarbonization (Furtado, 2019) means that if one heating option becomes unfeasible, there will be little left for the consumer to choose from and little remaining time for the other heating infrastructure to be rolled out. There is a clear need to increase awareness of the need to decarbonize and the technological options to transition to low-carbon heating. This need to raise awareness also extends to the possible benefits associated with low-carbon heating options beyond their environmental credentials, such as improved thermal comfort and possible improved health through the reduction of damp and mold in homes. Lowes and Woodman (2020) found that policy makers themselves perceive little benefit in heat decarbonization and that it is often viewed solely as disruptive and uncertain, which is likely a barrier to effective communication about possible benefits as outlined in this review.

Of course, benefits associated with improved thermal comfort and reduced bills are not guaranteed, and there is need to commission further research and carefully design policies that ensure solutions are tailored so that most people can take advantage of these benefits. At the very least, policies need to ensure different groups or communities are not disproportionally disadvantaged by a transition to low-carbon heating by tailoring technological solutions as much as possible. This should be a clear priority for further policy development in this area.

Given that installation and running costs were consistently raised by research participants as a primary concern for the switch to new heating systems, another crucial question is how the transformation to low-carbon heating will be managed and paid for. Cost considerations and especially the fair distribution of costs are likely to be a key aspect of acceptance of new forms of heating. Transforming the heating system will require a comprehensive policy and governance approach, which could include supporting and devolving budgetary and decision-making powers to local authorities to enable decentralized heat alternatives (for a systematic review of heat transformation research see Stabler & Foulds, 2020). Research on public perceptions of who should pay for energy transitions showed that members of the public assigned greater responsibility to the government and energy companies and did not believe they were currently contributing to costs sufficiently (Becker et al., 2019). Regarding ownership structures, some participants preferred privatization as they associated it with more choice, but others were in favor of reforms such as more regulation of tariffs or nationalization (Becker et al., 2019). The Centre for Alternative Technology suggests that key assets like the national grid could be brought back into public ownership and green investments could be supported by local or municipal banks and citizen finance. This highlights that changes need to reach far beyond the immediate and more obvious energy infrastructure (Centre for Alternative Technology, 2017; see also Stabler & Foulds, 2020).

It is also noteworthy that the previous successful gas rollout was government-led (Williams, 1981), whereas the current UK and devolved (Scotland, Wales, Northern Ireland) government strategies for the rollout of low-carbon heating rely heavily on consumer choice. A transformation of this scale is unlikely to succeed without concerted action and significant government involvement. Without financial support, many people will be unable to install new technologies or energy efficiency measures. It is therefore critical that the government implements long-term funding schemes and also ensures that the supply of a skilled workforce can meet the increasing demand for installation and long-term maintenance.

Finally, the above-raised points suggest that we cannot take for granted public perceptions and acceptance of low-carbon heating technologies, and that acceptance will depend on how well solutions are tailored to individual and local circumstances. This is particularly pertinent given there are still many uncertainties in the pathways to low-carbon heating in the UK, with many decisions still outstanding. To ensure public buy-in, much greater public engagement (beyond awareness raising) is likely needed, for example, involving people in strategic decision-making in terms of what broad pathways to pursue (e.g., green vs. blue hydrogen—if any) as well as local planning decisions on what solution is best suited to a particular area (e.g., Itten et al., 2021; Pidgeon et al., 2014).

In conclusion, future research and policy for the heat transition will need to consider the specific context of implementing low-carbon heating technologies and policies, the suitability for the local area, people's values, and how to support a fair process for the adoption of new technologies and practices. This review points to the ways in which such changes are not purely individual or simple technology choices, but are embedded in the fabric of society, infrastructure, and social life. This points to the need for a holistic approach to heat decarbonization in ways which can support people in transitioning to new heating systems.

AUTHOR CONTRIBUTIONS

Sarah Becker: Conceptualization (equal); writing – original draft (lead); writing – review and editing (equal). **Christina Demski:** Conceptualization (lead); funding acquisition (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (supporting). **William Smith:** Writing – review and editing (equal). **Nick Pidgeon:** Conceptualization (lead); funding acquisition (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (supporting).

ACKNOWLEDGMENTS

We would like to thank Dr. Richard Lowes and 2 anonymous reviewers for providing in-depth comments, edits, and feedback on this review.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

ORCID

Sarah Becker https://orcid.org/0000-0002-9557-4968
Christina Demski https://orcid.org/0000-0002-9215-452X
William Smith https://orcid.org/0000-0001-8688-4561
Nick Pidgeon https://orcid.org/0000-0002-8991-0398

RELATED WIREs ARTICLES

Public perceptions and governance of controversial technologies to tackle climate change: Nuclear power, carbon capture and storage, wind, and geoengineering
Household electricity consumers' incentive to choose dynamic pricing under different taxation schemes

ENDNOTES

[1] We acknowledge that there is no such thing as a homogenous group making up the "general public"—in perceptions of technologies and the environment multiple publics exist each with different histories, agendas, and cultural backgrounds (e.g., Pidgeon et al., 1992). We also use this term to describe members of the general public, as opposed to people who have a particular background or stake in heat decarbonization.

[2] The Climate Assembly UK examined public preferences for how to address climate change in the UK by bringing together people from different walks of life and facilitating discussion of how to reach net zero by 2050. Participants learned about climate change and possible ways for the UK to reduce emissions, discussed these options, and developed recommendations for action.

[3] The renewable heat premium payment scheme offered householders one-off payments to support them buying renewable heating technologies such as solar thermal panels and heat pumps. The scheme ran from 2011 to 2014.

[4] The renewable heat incentive is a UK Government scheme which provides financial incentives to promote renewable heat since 2014. Under the scheme people receive regular payments for 7 years based on estimates of how much their low-carbon heating system produces.

REFERENCES

Addario, G., Jessop, C., Mezzanzanica, M., & Wood, M. (2020). *Transforming heat—Public attitudes research. A survey of the GB public on the transition to a low-carbon heating future*. Report for BEIS by NatCen. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/913541/transforming-heat-public-attitudes-research-report.pdf

Ashworth, P., Witt, K., Ferguson, M., & Sehic, S. (2019). *Developing community trust in hydrogen*. Retrieved from https://energyministers.gov.au/sites/prod.energycouncil/files/publications/documents/nhs-developing-community-trust-in-hydrogen-report-2019_0.pdf

Association for Decentralised Energy. (2018). *Market report: Heat networks in the UK*. Retrieved from https://www.theade.co.uk/assets/docs/resources/Heat%20Networks%20in%20the%20UK_v5%20web%20single%20pages.pdf

Attari, S. Z., DeKay, M. L., Davidson, C. I., & De Bruin, W. B. (2010). Public perceptions of energy consumption and savings. *Proceedings of the National Academy of Sciences of the United States of America*, *107*, 16054–16059. https://doi.org/10.1073/pnas.1001509107

Becker, S., Demski, C., Evensen, D., & Pidgeon, N. (2019). Of profits, transparency, and responsibility: Public views on financing energy system change in the United Kingdom. *Energy Research and Social Science*, *55*, 236–246. https://doi.org/10.1016/j.erss.2019.05.013

Bellaby, P., Upham, P., Flynn, R., & Ricci, M. (2016). Unfamiliar fuel: How the UK public views the infrastructure required to supply hydrogen for road transport. *International Journal of Hydrogen Energy*, *41*, 6534–6543. https://doi.org/10.1016/j.ijhydene.2016.03.024

Bögel, P., Oltra, C., Sala, R., Lores, M., Upham, P., Dütschke, E., Schneider, U., & Wiemann, P. (2018). The role of attitudes in technology acceptance management: Reflections on the case of hydrogen fuel cells in Europe. *Journal of Cleaner Production*, *188*, 125–135. https://doi.org/10.1016/j.jclepro.2018.03.266

Boydell, R. (2021). Heat and buildings strategy: The good, bad and ugly of the UK's plan to replace gas boilers. *The Conversation*. Retrieved from https://theconversation.com/heat-and-buildings-strategy-the-good-bad-and-ugly-of-the-uks-plan-to-replace-gas-boilers-170227

Brown, P., Swan, W., & Chahal, S. (2014). Retrofitting social housing: Reflections by tenants on adopting and living with retrofit technology. *Energy Efficiency*, *7*, 641–653. https://doi.org/10.1007/s12053-013-9245-3

Butler, C., Demski, C. C., Parkhill, K. A., & Pidgeon, N. F. (2015). Public values for energy futures: framing, indeterminacy and policy making. *Energy Policy*, *87*, 665–672.

Caird, S., Roy, R., & Potter, S. (2012). Domestic heat pumps in the UK: User behaviour, satisfaction and performance. *Energy Efficiency*, *5*, 283–301.

Calver, P., Mander, S., & Abi Ghanem, D. (2022). Low carbon system innovation through an energy justice lens: Exploring domestic heat pump adoption with direct load control in the United Kingdom. *Energy Research and Social Science*, *83*, 102299.

Carter, S., Williamson, G., King, J., Levi, V., & Mcwilliam, J. (2017). Key findings of DS2030—A study into future GB distribution network operations. *CIRED—Open Access Proceedings Journal*, *2017*, 2390–2393. https://doi.org/10.1049/oap-cired.2017.0947

Cebon, D. (2020). *Hydrogen for heating?* Retrieved from https://www.csrf.ac.uk/blog/hydrogen-for-heating/

Centre for Alternative Technology. (2017). *Zero carbon Britain: Making it happen, Report in short*. https://doi.org/10.1300/J009v18n01_07

Chapman, O., Kapetaniou, C., & Gabriel, M. (2021). *Decarbonising homes: Consumer attitudes towards energy efficiency and green heating in the UK*. Nesta. Retrieved from https://apo.org.au/sites/default/files/resource-files/2021-06/apo-nid312865.pdf

Chappells, H., & Shove, E. (2005). Debating the future of comfort: Environmental sustainability, energy consumption and the indoor environment. *Building Research and Information*, *33*, 32–40. https://doi.org/10.1080/0961321042000322762

Cherryman, S. J., King, S., Hawkes, F. R., Dinsdale, R., & Hawkes, D. L. (2008). An exploratory study of public opinions on the use of hydrogen energy in Wales. *Public Understanding of Science*, *17*, 397–410. https://doi.org/10.1177/0963662506068053

Chilvers, J., Bellamy, R., Pallett, H., & Hargreaves, T. (2021). A systemic approach to mapping participation with low-carbon energy transitions. *Nature Energy*, *6*(3), 250–259. https://doi.org/10.1038/s41560-020-00762-w

Climate Assembly UK. (2020). *The path to net zero*. Retrieved from https://www.climateassembly.uk/recommendations/index.html

Committee on Climate Change (CCC). (2018). *Hydrogen in a low-carbon economy*. pp. 1–128. Retrieved from https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

Committee on Climate Change (CCC). (2020). *The sixth carbon budget: The UK's path to net zero*. Retrieved from https://www.theccc.org.uk/publication/sixth-carbon-budget/

Committee on Climate Change (CCC). (2021). *Independent assessment: The UK's net zero strategy*. Retrieved from https://www.theccc.org.uk/wp-content/uploads/2021/10/Independent-Assessment-of-the-UK-Net-Zero-Strategy-CCC.pdf

Crawley, C., Johnson, C., Calver, P., & Fell, M. J. (2021). *Demand response: success isn't just about numbers. CREDS Policy brief 016*. Centre for Research into Energy Demand Solutions Retrieved from https://www.creds.ac.uk/wp-content/uploads/CREDS-demand-response-briefing.pdf

De Best-Waldhober, M., Peuchen, R., & Weeda, M. (2013). Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe. *HyUnder*. Retrieved from https://publications.tno.nl/publication/34632215/52KW3o/o13047.pdf

Demski, C., Cherry, C., & Verfuerth, C. (2022). *The road to net zero: UK public preferences for low-carbon lifestyles*. Centre for Climate Change and Social Transformations (CAST). Retrieved from https://researchportal.bath.ac.uk/en/publications/the-road-to-net-zero-uk-public-preferences-for-low-carbon-lifesty

Demski, C., Steentjes, K., & Poortinga, W. (2022). *Public worry about climate change and energy security in the cost-of-living crisis*. CAST Briefing 17.

Demski, C., Thomas, G., Becker, S., Evensen, D., & Pidgeon, N. (2019). Acceptance of energy transitions and policies: Public conceptualisations of energy as a need and basic right in the United Kingdom. *Energy Research and Social Science*, *48*, 33–45. https://doi.org/10.1016/j.erss.2018.09.018

Department of Business Energy & Industrial Strategy. (2017a). *RHI evaluation synthesis*. Retrieved from https://www.gov.uk/government/publications/rhi-evaluation-synthesis-report

Department of Business Energy & Industrial Strategy. (2017b). *Census of owner-occupier applicants to the domestic RHI*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642097/Domestic_Census_waves_1-24.pdf

Department of Business Energy & Industrial Strategy. (2018). *Clean growth: Transforming heating—Overview of current evidence*. Retrieved from https://www.gov.uk/government/publications/heat-decarbonisation-overview-of-current-evidence-base

Department of Business Energy & Industrial Strategy. (2020). *Energy white paper: Powering our net zero future*. Retrieved from https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

Department of Business Energy & Industrial Strategy. (2021a). *Heat and buildings strategy*. Retrieved from https://www.gov.uk/government/publications/heat-and-buildings-strategy

Department of Business Energy & Industrial Strategy. (2021b). *Net zero strategy: Build back greener*. Retrieved from https://www.gov.uk/government/publications/net-zero-strategy

Department of Business Energy & Industrial Strategy. (2021c). *Climate change and net zero: Public awareness and perceptions*. Retrieved from https://www.gov.uk/government/publications/climate-change-and-net-zero-public-awareness-and-perceptions

Department of Business Energy & Industrial Strategy. (2022). BEIS Public Attitudes Tracker: Autumn 2022. Retrieved from https://www.gov.uk/government/statistics/beis-public-attitudes-tracker-autumn-2022

Department of Energy & Climate Change. (2016). Qualitative research with domestic RHI owner occupier applicants. Retrieved from https://www.gov.uk/government/publications/qualitative-research-with-domestic-rhi-owner-occupier-applicants

Edwards, R. L., Font-Palma, C., & Howe, J. (2021). The status of hydrogen technologies in the UK: A multi-disciplinary review. *Sustainable Energy Technologies and Assessments*, *42*, 100901.

Element Energy. (2021). *Development of trajectories for residential heat decarbonisation to inform the sixth carbon budget*. A Study for the Committee on Climate Change. Retrieved from: https://www.theccc.org.uk/wp-content/uploads/2020/12/Full-Report-Development-of-trajectories-for-residential-heat-decarbonisation-to-inform-the-Sixth-Carbon-Budget-Element-Energy.pdf

Energy Saving Trust. (2013). *The heat is on: heat pump field trials phase 2*. Retrieved from https://energysavingtrust.org.uk/sites/default/files/reports/TheHeatisOnweb%281%29.pdf

Energy Systems Catapult. (2022). *BEIS electrification of heat: Participant recruitment report*. Retrieved from https://es.catapult.org.uk/report/electrification-of-heat-participant-recruitment-report/

Energy Technologies Institute. (2015). *Smart systems and heat: Consumer challenges for low carbon heat*. Retrieved from https://www.eti.co.uk/library/smart-systems-and-heat-consumer-challenges-for-low-carbon-heat

Energy Technologies Institute. (2018). *How can people get the heat they want at home, without the carbon?* Retrieved from https://www.eti.co.uk/insights/how-can-people-get-the-heat-they-want-without-the-carbon

Finkel, A., Amal, R., Archer, B., Ashworth, P., Andrew, D., Frischknecht, I., Hablutzel, M., Johnson, C., Lawson, M., Mayfield, P., & Wilson, B. (2018). *Hydrogen for Australia's future*. Hydrogen Strategy Group, Commonwealth of Australia. https://www.chiefscientist.gov.au/sites/default/files/HydrogenCOAGWhitePaper_WEB.pdf

Flynn, R., Bellaby, P., & Ricci, M. (2006). Risk perception of an emergent technology: The case of hydrogen energy. *Forum Qualitative Sozialforschung*, *7*, 28–29.

Flynn, R., Bellaby, P., & Ricci, M. (2009). The "value-action gap" in public attitudes towards sustainable energy: The case of hydrogen energy. *The Sociological Review*, *57*(Suppl 2), 159–180. https://doi.org/10.1111/j.1467-954X.2010.01891.x

Freedom Project. (2018). *Freedom project final report*. Retrieved from https://www.wwutilities.co.uk/media/2829/freedom-project-final-report-october-2018.pdf

Fu, E., & Abbassian, L. (2018). *Qualitative research: Heat networks*. Kantar Public. Retrieved from https://assets.publishing.service.gov.uk/media/5af31072e5274a25edd32626/Kantar_consumer_research_heat_networks.pdf

Furtado, J. (2019). *Uncomfortable home truths: Why Britain urgently needs a low carbon heat strategy*. Policy Connect. Retrieved from https://www.policyconnect.org.uk/research/uncomfortable-home-truths-future-gas-series-part-3

Fylan, F., Fletcher, M., & Christmas, S. (2020). *H21: Public perceptions of converting the gas network to hydrogen*. Leeds Beckett University: 2020. Retrieved from https://h21.green/projects/h21-social-science-research/

Gilbertson, J., Stevens, M., Stiell, B., & Thorogood, N. (2006). Home is where the hearth is: Grant recipients' views of England's home energy efficiency scheme (warm front). *Social Science and Medicine*, *63*, 946–956. https://doi.org/10.1016/j.socscimed.2006.02.021

Goodchild, B., Ambrose, A., & Maye-banbury, A. (2017). Energy Research & Social Science Storytelling as oral history: Revealing the changing experience of home heating in England. *Energy Research & Social Science*, *31*, 137–144. https://doi.org/10.1016/j.erss.2017.06.009

Gordon, J. A., Balta-Ozkan, N., & Nabavi, S. A. (2022a). Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition. *Renewable and Sustainable Energy Reviews*, *164*, 112481. https://doi.org/10.1016/j.rser.2022.112481

Gordon, J. A., Balta-Ozkan, N., & Nabavi, S. A. (2022b). Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance. *Applied Energy*, *324*, 119715. https://doi.org/10.1016/j.apenergy.2022.119715

Gray, D., Snodin, H., & Bullen, A. (2019). *Exploring the evidence on potential issues associated with trialling hydrogen heating in communities. A literature review and focus group study*. Department for Business, Energy and Industrial Strategy.

Greater London Authority. (2018). *Communal heating consumer survey*. Retrieved from: communal_heating_consumer_survey_final.pdf (london.gov.uk).

Groves, C., Henwood, K., Butler, C., Parkhill, K. A., Shirani, F., & Pidgeon, N. F. (2016). Invested in unsustainability? On the psychosocial patterning of engagement in practices. *Environmental Values*, *25*(3), 309–328.

Hanmer, C., Shipworth, M., Shipworth, D., & Carter, E. (2019). How household thermal routines shape UK home heating demand patterns. *Energy Efficiency*, *12*, 5–17. https://doi.org/10.1007/s12053-018-9632-x

Hanna, R., Parrish, B., & Gross, R. (2016). *Best practice in heat decarbonisation policy: A review of the international experience of policies to promote the uptake of low-carbon heat supply*. UKERC Working Paper. Retrieved from https://ukerc.ac.uk/project/best-practice-in-heat-decarbonisation-policy/

Hansson, A., Anshelm, J., Fridahl, M., & Haikola, S. (2022). The underworld of tomorrow? How subsurface carbon dioxide storage leaked out of the public debate. *Energy Research & Social Science*, *90*, 102606. https://doi.org/10.1016/j.erss.2022.102606

Hanusch, F., & Schad, M. (2021). Hydrogen research: technology first, society second? *Ecological Perspectives for Science and Society*, *30*, 82–86.

Henwood, K. L., Pidgeon, N. F., Groves, C., Shirani, F., Butler, C., & Parkhill, K. (2015). *Energy biographies: Final research report*. Cardiff University. Retrieved from https://orca.cardiff.ac.uk/87333/

Heptonstall, P., & Winskel, M. (2021). Expectations and sources of cost reduction in low/zero carbon domestic heat technologies: the case of heat pumps. *UKERC Project Scoping Note*. Retrieved from: https://ukerc.ac.uk/project/heat-pump-cost-reductions/

Hodges, N., Goaman, D., & Smith, K. (2018). *Qualitative research with consumers and operators of heat networks*. Centre for Sustainable Energy. Retrieved from https://www.cse.org.uk/downloads/reports-and-publications/fuel-poverty/insulation-and-heating/energy-justice/building-performance/qualitative-research-with-consumers-and-operators-of-heat-networks-dec-2018.pdf

Hy4Heat. (2020). *Hy4Heat information*. Retrieved from https://www.hy4heat.info/

International Energy Agency. (2021). *District heating*. International Energy Agency Retrieved from https://www.iea.org/reports/district-heating

Ipsos Mori and Energy Saving Trust. (2013). *Homeowners' willingness to take up more efficient heating systems*. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191541/More_efficient_heating_report_2204.pdf

Itten, A., Sherry-Brennan, F., Hoppe, T., Sundaram, A., & Devine-Wright, P. (2021). Co-creation as a social process for unlocking sustainable heating transitions in Europe. *Energy Research and Social Science*, *74*, 101956.

Judson, E., Bell, S., Bulkeley, H., Powells, G., & Lyon, S. (2015). The co-construction of energy provision and everyday practice: Integrating heat pumps in social housing in England. *Science and Technology Studies*, *28*, 26–53.

Kerr, N., Gouldson, A., & Barrett, J. (2018). Holistic narratives of the renovation experience: Using Q-methodology to improve understanding of domestic energy retrofits in the United Kingdom. *Energy Research and Social Science*, *42*, 90–99. https://doi.org/10.1016/j.erss.2018.02.018

Kerr, N., & Winskel, M. (2022). Have we been here before? Reviewing evidence of energy technology phase-out to inform home heating transitions. *Energy Research and Social Science*, *89*, 1026–1040.

Kuijer, L., & Watson, M. (2017). 'That's when we started using the living room': Lessons from a local history of domestic heating in the United Kingdom. *Energy Research and Social Science*, *28*, 77–85. https://doi.org/10.1016/j.erss.2017.04.010

Leber, R. (2021). How the fossil fuel industry convinced Americans to love gas stoves. Mother Jones. Retrieved from https://www.motherjones.com/environment/2021/06/how-the-fossil-fuel-industry-convinced-americans-to-love-gas-stoves/

Lennon, B., Dunphy, N., Gaffney, C., Revez, A., Mullally, G., & O'Connor, P. (2019). Citizen or consumer? Reconsidering energy citizenship. *Journal of Environmental Policy & Planning*, *22*(2), 184–197. https://doi.org/10.1080/1523908x.2019.1680277

Lichtenstein, S., & Slovic, P. (2006). *The construction of preference*. Cambridge University Press.

Liu, S., Shukla, A., & Zhang, Y. (2014). Investigations on the integration and acceptability of GSHP in the UK dwellings. *Building and Environment*, *82*, 442–449. https://doi.org/10.1016/j.buildenv.2014.09.020

L'Orange Seigo, S., Dohle, S., & Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews*, *38*, 848–863.

Lowe, R., & Oreszczyn, T. (2020). *Building decarbonisation transition pathways: Initial reflections. CREDS Policy brief 013*. Centre for Research into Energy Demand Solutions Retrieved from https://www.creds.ac.uk/wp-content/uploads/CREDS-decarb-transitions-brief-2020.pdf

Lowe, R., Summerfield, A., Oikonomou, E., Love, J., Biddulph, P., Gleeson, C., Chiu, L. F., & Wingfield, J. (2017). *Final report on analysis of heat pump data from the renewable heat premium payment (RHPP) scheme*. UCL Energy Institute Retrieved from https://pdfs.semanticscholar.org/3d4e/98b976658328180582deb5c32e1e447fa4d9.pdf

Lowes, R., & Woodman, B. (2018). *Incumbency in the UK heat sector and implications for the transformation towards low-carbon heating*. UKERC Working Paper Retrieved from https://ukerc.ac.uk/publications/incumbency-in-the-uk-heat-sector/

Lowes, R., & Woodman, B. (2020). Disruptive and uncertain: Policy makers' perceptions on UK heat decarbonisation. *Energy Policy*, *142*, 111494. https://doi.org/10.1016/j.enpol.2020.111494

Lowes, R., Woodman, B., & Speirs, J. (2020). Heating in Great Britain: An incumbent discourse coalition resists an electrifying future. *Environmental Innovation and Societal Transitions*, *37*, 1–17. https://doi.org/10.1016/j.eist.2020.07.007

Majumder-Russell, D., Rihoy, C., & Mitchell, K. (2021). *Hydrogen law and regulation in the United Kingdom*. CMS Retrieved from https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-kingdom

Milne, S., Chambers, K., Elks, S., Hussain, B., & McKinnon, S. (2019). Living carbon free: Exploring what a net-zero target means for households. *Energy systems catapult*. Retrieved from https://www.theccc.org.uk/publication/living-carbon-free-energy-systems-catapult/

Ministry of Housing, Communities & Local Government. (2020). *English housing survey 2019 to 2020*. Retrieved from: https://www.gov.uk/government/statistics/english-housing-survey-2019-to-2020-headline-report

O'Sullivan, K., Shirani, F., Pidgeon, N. F., & Henwood, K. L. (2022). Why active buildings? Realising the potentials of energy networked homes: a social scientific perspective. In V. Vahidinasab & B. Mohammadi-Ivatloo (Eds.), *Active building energy systems*. Springer. https://doi.org/10.1007/978-3-030-79742-3_2

Ozaki, R. (2018). Follow the price signal: People's willingness to shift household practices in a dynamic time-of-use tariff trial in the United Kingdom. *Energy Research and Social Science*, *46*, 10–18. https://doi.org/10.1016/j.erss.2018.06.008

Palmer, J., & Cooper, I. (2012). *United Kingdom housing energy fact file*. Department of Energy and Climate Change. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/201167/uk_housing_fact_file_2012.pdf

Peñaloza, D., Mata, É., Fransson, N., Fridén, H., Samperio, Á., Quijano, A., & Cuneo, A. (2022). Social and market acceptance of photovoltaic panels and heat pumps in Europe: A literature review and survey. *Renewable and Sustainable Energy Reviews*, *155*, 111867. https://doi.org/10.1016/j.rser.2021.111867

Phillips, A., & Seaford, C. (2021). *The climate consensus: The public's views on how to cut emissions*. DEMOS Retrieved from https://demos.co.uk/project/the-climate-consensus-the-publics-views-on-how-to-cut-emissions/

Pidgeon, N. (2020). Engaging publics about environmental and technology risks: frames, values and deliberation. *Journal of Risk Research*, *24*(1), 28–46. https://doi.org/10.1080/13669877.2020.1749118

Pidgeon, N., Kasperson, R., & Slovic, P. (Eds.). (2003). *Social amplification of risk*. Cambridge University Press.

Pidgeon, N. F., Demski, C. C., Butler, C., Parkhill, K. A., & Spence, A. (2014). Creating a national citizen engagement process for energy policy. *Proceedings of the National Academy of Sciences of the USA*, *111*(Suppl 4), 13606–13613. https://doi.org/10.1073/pnas.1317512111

Pidgeon, N. F., Groves, C., Cherry, C., Thomas, G., Shirani, F., & Henwood, K. L. (2022). 'A little self-sufficient town close to the beach': local energy system transformation through the lens of place and public things. In J. Webb, M. Tingey, F. Wade, et al. (Eds.), *Research handbook of energy and society*. Edward Elgar.

Pidgeon, N. F., Hood, C., Jones, D., Turner, B., & Gibson, R. (1992). Risk Perception. In *Risk—Analysis, perception and management: Report of a Royal Society Study Group* (pp. 89–134). The Royal Society.

Prior, A. (2019). *Public attitudes on clean growth*. Retrieved from https://sciencewise.org.uk/wp-content/uploads/2019/06/Public-attitudes-on-clean-growth_full-report-May-2019.pdf

Quarton, C., & Samsatli, S. (2020). Should we inject hydrogen into gas grids? Practicalities and whole-system value chain optimisation. *Applied Energy*, *275*, 115172. https://doi.org/10.1016/j.apenergy.2020.115172

Ricci, M., Bellaby, P., & Flynn, R. (2008). What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. *International Journal of Hydrogen Energy*, *33*, 5868–5880. https://doi.org/10.1016/j.ijhydene.2008.07.106

Ricci, M., Newsholme, G., Bellaby, P., & Flynn, R. (2006). Hydrogen: Too dangerous to base our future upon? *Institution of Chemical Engineers Symposium Series*, *151*, 42–60.

Rogers-Hayden, T., & Pidgeon, N. F. (2007). Moving engagement "upstream"? Nanotechnologies and the Royal Society and Royal Academy of Engineering inquiry. *Public Understanding of Science*, *16*, 346–364.

Scott, M., & Powells, G. (2019). *Blended hydrogen: The UK public's perspective*. Retrieved from https://www.ncl.ac.uk/media/wwwnclacuk/geographypoliticsandsociology/files/news/blended-hydrogen-the-uk-publics-perspective.pdf

Scott, M., & Powells, G. (2020). Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment. *Energy Research & Social Science*, *6*, 101346. https://doi.org/10.1016/j.erss.2019.101346

Scovell, M. D. (2022). Explaining hydrogen energy technology acceptance: A critical review. *International Journal of Hydrogen Energy*, *47*(19), 10441–10459. https://doi.org/10.1016/j.ijhydene.2022.01.099

Sherry-Brennan, F., Devine-Wright, H., & Devine-Wright, P. (2010). Public understanding of hydrogen energy: A theoretical approach. *Energy Policy*, *38*, 5311–5319. https://doi.org/10.1016/j.enpol.2009.03.037

Shirani, F., Groves, C., Butler, C., Parkhill, K. A., Henwood, K., & Pidgeon, N. (2017). Critical moments? Life transitions and energy biographies. *Geoforum*, *86*, 86–92.

Shirani, F., Groves, C., Henwood, K. L., Pidgeon, N. F., Roberts, E., & Thomas, G. (2020). *Mine water heating in Caerau: Thoughts from local residents*. FLEXIS (Flexible Integrated Energy Systems) Project Report, Cardiff University Accessed from https://orca.cardiff.ac.uk/id/eprint/138639/

Shirani, F., O'Sullivan, K., Hale, R., Pidgeon, N. F., & Henwood, K. L. (2022). From active houses to active homes: Understanding resident experiences of transformational design and social innovation. *Energies*, *15*, 7441. https://doi.org/10.3390/en15197441

Shirani, F., O'Sullivan, K., Henwood, K. L., Hale, R., & Pidgeon, N. F. (2022). Learning to live in an active home: household dynamics and unintended consequences. *Buildings and Cities*, *3*(1), 589–604. https://doi.org/10.5334/bc.216

Shrum, T. R., Markowitz, E., Buck, H., Gregory, R., van der Linden, S., Attari, S. Z., & Van Boven, L. (2020). Behavioural frameworks to understand public perceptions of and risk response to carbon dioxide removal. *Interface Focus*, *10*, 20200002. https://doi.org/10.1098/rsfs.2020.0002

Sovacool, B. K., Demski, C., & Noel, L. (2021). Beyond climate, culture and comfort in European preferences for low-carbon heat. *Global Environmental Change*, *66*, 102200. https://doi.org/10.1016/j.gloenvcha.2020.102200

Spence, A., Leygue, C., Wickes, L., Withers, L., Goulden, M., & Wardman, J. K. (2021). Dumber energy at home please: Perceptions of smart energy technologies are dependent on home, workplace, or policy context in the United Kingdom. *Energy Research & Social Science*, *75*, 102021. https://doi.org/10.1016/j.erss.2021.102021s

Stabler, L., & Foulds, C. (2020). *Governing the UK's transition to decarbonised heating: Lessons from a systematic review of past and ongoing heat transitions*. Retrieved from https://ukerc.ac.uk/publications/governing-the-uks-transition-to-decarbonised-heating-lessons-from-a-systematic-review-of-past-and-ongoing-heat-transitions/

Steentjes, K., Poortinga, W., Demski, C., & Whitmarsh, L. (2021). UK perceptions of climate change and lifestyle changes. CAST Briefing Paper 08. Retrieved from https://cast.ac.uk/wp-content/uploads/2021/03/CAST-Briefing-08.pdf

Sweetnam, T., Fell, M., Oikonomou, E., & Oreszczyn, T. (2019). Domestic demand-side response with heat pumps: Controls and tariffs. *Building Research & Information*, *47*, 344–361. https://doi.org/10.1080/09613218.2018.1442775

The Carbon Trust & Rawlings Support Services. (2016). *Evidence gathering—Low carbon heating technologies*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565241/Domestic_Hybrid_Heat_Pumps_-_FINAL.pdf

Thomas, G., Pidgeon, N., & Henwood, K. (2022). *Hydrogen, a less disruptive pathway for domestic heat? Lessons from public perceptions research*. Cleaner Production Letters.

Thomas, G., Pidgeon, N., & Roberts, E. (2018). Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom. *Energy Research and Social Science*, *46*, 1–9. https://doi.org/10.1016/j.erss.2018.06.007

Thornton, A., Newton, S., Andersson, D., Witso, C., Matthews, P., & Taylor, L. (2017). *Heat networks consumer survey: A report for BEIS by Kantar Public*. Department of Business, Energy and Industrial Strategy.

UK Government. (2019). *Net zero review launched to support UK's world leading climate commitment—GOV.UK*. Retrieved from https://www.gov.uk/government/news/net-zero-review-launched-to-support-uks-world-leading-climate-commitment

Upham, P., & Jones, C. (2012). Don't lock me in: Public opinion on the prospective use of waste process heat for district heating. *Applied Energy*, *89*, 21–29. https://doi.org/10.1016/j.apenergy.2011.02.031

Walker, G. (2014). The dynamics of energy demand: Change, rhythm and synchronicity. *Energy Research and Social Science*, *1*, 49–55. https://doi.org/10.1016/j.erss.2014.03.012

Whitmarsh, L., Steentjes, K., Poortinga, W., Beaver, K., Gray, E., Skinner, G., & Thompson, S. (2021). *UK public support for net zero policies*. CAST Briefing Paper 9.

Williams, H., Lohmann, T., Foster, S., & Morrell, G. (2018). Public acceptability of the use of hydrogen for heating and cooking in the home. Retrieved from https://www.theccc.org.uk/wp-content/uploads/2018/11/Public-acceptability-of-hydrogen-in-the-home-Full-report.pdf

Williams, T. I. (1981). *A history of the British Gas Industry*. Oxford University Press.

Wilson, G., Taylor, R., & Rowley, P. (2018). Challenges for the decarbonisation of heat: Local gas demand vs electricity supply Winter 2017/2018. *UKERC Briefing Note*. Retrieved from http://www.ukerc.ac.uk/publications/local-gas-demand-vs-electricity-supply.html

Zaunbrecher, B. S., Arning, K., Falke, T., & Ziefle, M. (2016). No pipes in my backyard?: Preferences for local district heating network design in Germany. *Energy Research and Social Science*, *14*, 90–101. https://doi.org/10.1016/j.erss.2016.01.008

How to cite this article: Becker, S., Demski, C., Smith, W., & Pidgeon, N. (2023). Public perceptions of heat decarbonization in Great Britain. *WIREs Energy and Environment*, e492. https://doi.org/10.1002/wene.492