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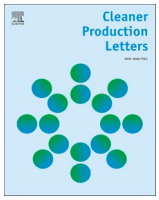

# Hydrogen, a less disruptive pathway for domestic heat? Exploratory findings from public perceptions research

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ABSTRACT

The disruption associated with heat decarbonisation has been identified as a key opportunity for hydrogen technologies in temperate countries and regions where established distribution infrastructure and familiarity with natural gas boilers predominate. A key element of such claims is the empirically untested belief that citizens will prefer to minimise disruption and perceive hydrogen to be less disruptive than the network upgrades and retrofit measures needed to support electric and other low carbon heating technologies. This article reports on exploratory deliberative research with residents of Cardiff, Wales which examined public perceptions of heating disruptions. Our findings suggest that concerns over public responses to disruption may be overstated, particularly as they relate to construction and road excavation for network upgrade. Disruptions arising from permanent changes to building fabric may be more problematic for heat pump retrofit, however these may be greatly overshadowed by anxieties over the cost implications of moving to hydrogen fuel. Furthermore, the biographical patterning of citizen preferences raises significant questions for hydrogen roll-out strategies relying on regionalised network conversion. We conclude by arguing that far from a non-disruptive alternative to electrification, hydrogen risks being seen as posing substantial disruptions to precarious household finances and lifestyles.

## 1. Introduction

While hydrogen has long been associated with decarbonisation in heavy industry, transport and the power sector, in recent years it has also emerged as an option for domestic heat decarbonisation in several countries including France, Germany, Japan and the United Kingdom (UK) (IEA, 2019). However the potential scope for hydrogen heating remains unclear. Doubts remain over the cost, environmental implications and feasibility of generating and transporting sufficient hydrogen to meet decarbonisation targets, even when relying on hydrogen production from fossil fuels (Committee on Climate Change, 2016; Rosenow and Lowes, 2020; van Renssen, 2020). Never-the-less, whole-system analyses have identified a potential role for hydrogen either in hybrid heat pump applications where it may defer the need for more substantial home retrofit and network upgrade measures, or as part of local or regional heating strategies where gas network conversion to hydrogen is made more feasible due to nearby production infrastructure or demand from industry (Element Energy and E4Tech, 2018; European Parliament Research Service, 2021; IEA, 2022; Strbac et al., 2018).

Today, many heating markets around the world remain locked into natural gas fired central heating (Gross and Hanna, 2019). Of these, the UK is the paradigmatic example, combining a mature and near-ubiquitous gas network with a thermally inefficient building stock dependent on gas boilers to meet expectations of thermal comfort. For over a decade, electrification has been seen as the primary vector for heat decarbonisation around the world, particularly in areas unsuited to district heating (Lucon et al., 2014). However we are now seeing a growing awareness that electrification may entail substantial disruptions to electricity networks (Element Energy, 2021; European Parliament Research Service, 2021; MacLean et al., 2016), domestic building fabric and heating practices (de Wilde, 2020; Gram-Hanssen, 2010; Lowe et al., 2018). It is into this space that advocacy coalitions comprising incumbent gas networks and boiler manufacturers have positioned hydrogen as a less disruptive decarbonisation solution; emphasising the ready availability of infrastructure, technical and performance characteristics analogous to the dominant natural gas boiler, and the low upfront costs of boiler technologies relative to heat pumps (Lowes et al., 2020).

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Hydrogen advocates frame the technology as a consumer friendly alternative to construction intensive heat pump retrofit and electricity network upgrades (EUA, 2017). Significant attention has been paid to the capacity to convert local or regional gas distribution infrastructure to hydrogen (Northern Gas Networks Wales & West Utilities Kiwa Amec Foster Wheeler, 2019), a process which could cluster around hydrogen production infrastructure and potential industrial users, stimulating hydrogen markets on a regional basis while production ramps up (European Parliament Research Service, 2021; HM Government, 2021). Such narratives dovetail with policy maker concerns over heat decarbonisation as a 'disruptive and uncertain' process, entailing costs and material changes for which few citizens are expected to be grateful (Lowes and Woodman, 2020). In the UK, the result has been a delay in the development of policies and supply chains for heat decarbonisation, in anticipation of a strategic decision over hydrogen due to be taken in 2026 (Climate Change Committee, 2023).

Our aim here is not to question or debunk the feasibility of using hydrogen in domestic heating, or to resolve a zero-sum competition between electric and hydrogen heat pathways. Rather we aim to test the claim that hydrogen represents a less disruptive option by empirically examining the extent to which lay citizens do or do not perceive hydrogen as disruptive. Drawing on qualitative data from deliberative workshops held with members of the public in Cardiff, Wales, we examine how citizens perceive the disruptions attendant to heat decarbonisation, and how these might impact the acceptability of hydrogen as a domestic heating fuel. Such questions are important not only because they appear to be acting as a break on policy making, but also because acceptability to diverse publics has long been understood as shaping technology uptake and popular support for low carbon policies and infrastructure (Apt and Fischhoff, 2006; Pidgeon, 2021; Wolsink, 2018). By examining disruption from the standpoint of public perceptions we address the following research questions.

1) To what extent do lay perceptions of disruption impact the acceptability of heat decarbonisation?
2) What (if any) aspects of hydrogen heating do lay citizens perceive to be disruptive?
3) Is hydrogen likely to perceived as a less disruptive route to heat decarbonisation than other technologies?

Our findings suggest that far from a less disruptive option, our participants perceived hydrogen as presenting different forms of disruption, particularly in terms of its potential costs and for longer duration disconnections during conversion processes. We conclude by outlining some conditions under which our participants felt hydrogen and hybrid heating strategies may be more acceptable and reflecting on the role of disruption in the discursive strategies of industry incumbents.

## 2. Literature review

Perceptions research examining heat decarbonisation has for some time emphasised the hassle, inconvenience, or disruption attendant to boiler replacement as mitigating against uptake of low carbon heating (Beaglehole and Patel, 2016; BEIS, 2020; Ipsos MORI and Energy Saving Ipsos MORI, Energy Saving Trust, 2013). At its most basic level disruption can be separated into temporary disruptions coinciding with installation and construction, and more permanent disruptions to living space and heating practices (Climate Citizens and Lancaster University, 2022). Analysis conducted for the Department of Business, Energy and Industrial Strategy in 2020 likewise found higher levels of disruption to impact the acceptability of heat decarbonisation options, although the effect size was small (BEIS, 2020). Indeed, across such studies disruption has consistently appeared to be of lower priority than cost and responsibility for heating upgrades in shaping acceptability. Such findings reflect the well-known insight from environmental psychology that situational variables such as cost, income, responsibility and infrastructure availability mediate and constrain attitudes and intentions towards pro-environmental behaviours (Barr, 2007). Given the importance of cost, the relatively low upfront costs of hydrogen boilers may be seen as an opportunity by some citizens to decarbonise their heating systems with lower capital outlay. However, such perceptions may be tempered by the higher running costs attendant on using hydrogen as a fuel (Rosenow and Lowes, 2020), and reliance on a gas network operating at lower levels of utilisation as more homes switch to electric heating (NEA, 2017).

While disruption has often been seen as of secondary importance in shaping heating preferences, few studies have extended their view of disruption beyond the home to energy networks, which may require significant upgrades to support electrification. These can include the replacement of or installation of new substations; excavation to reinforce low voltage networks, and upgrades to service cables connecting homes to the network (EA Technologies, 2012; Element Energy, 2021; Strbac et al., 2018). Little perceptions research exists on network reinforcement at the distribution scale, but on high-voltage networks reinforcement has been perceived to pose significant disruptions to place and landscape attachments, with perceived risks of electromagnetic radiation further undermining feelings of safety and security (Aas et al., 2017; Cotton and Devine-Wright, 2013; Poortinga et al., 2008). By contrast, the ongoing iron mains replacement programme (2002–2032), is expected to render the majority of the UK's gas distribution infrastructure hydrogen ready. Disruption from this work has been limited by its elongated schedule, and horizontal insertion techniques that allow pipe replacement with minimal excavation. Disruption may however be expected at the moment of conversion where phased shutdowns will be needed to facilitate domestic conversions, venting of residual natural gas and re-pressurisation with hydrogen (Northern Gas Networks Wales & West Utilities Kiwa Amec Foster Wheeler, 2019). This could entail the disconnection of domestic gas supplies for up to a week. Given that choice over timing is likely to be limited under such circumstances, there is significant potential for the conversion process to be perceived as unduly disruptive if appropriate mitigation measures are not in place (Williams et al., 2018).

Furthermore, given public unfamiliarity with low carbon heating technologies, it is possible survey research has understated the relative importance of disruption, measuring unstable 'pseudo opinions' (Malone et al., 2010) subject to change when contextualised more explicitly around changes to home and everyday life. We might expect domestic frames to be particularly powerful given association of the home with feelings of safety, biographical and personal identity (Gram-Hanssen and Darby, 2018; Harris, 2017). The acceptability of disruptions may thus look quite different when considered in the context of specific homes and places in which identities and anticipated life course trajectories become invested (Roberts and Henwood, 2019; Sunikka-Blank and Galvin, 2016). The importance of such identifications is recognised implicitly in the protections granted to heritage homes or those in protected landscapes which restrict heat pump installation in some instances (Green et al., 2020). These, along with potential losses of living space and constraints on energy efficiency and hot water tank retrofit in older and smaller properties have been identified as key categories of dwelling that may be better suited to hybrid gas or hydrogen heating (EUA, 2021; Freedom Project, 2018).

User experience studies of heat pump installation have often been characterised by disruptions to psycho-socially important heating, ventilation and caregiving practices (cf. Sovacool et al., 2020). Others have noted how the impacts of construction, poor quality information or installation may disproportionately disrupt the lives of vulnerable groups such as the chronically ill, elderly, and low income households-potentially raising questions over the fairness and legitimacy of decarbonisation programmes (Calver et al., 2022; Ellis et al., 2015; Topouzi, 2016). Everyday challenges posed by the disruptive potentials of decarbonisation in practice can be impactful at the level of lived experiences (Groves et al., 2016; Shirani et al., 2021; Sovacool

et al., 2020) although its psychosocial aspects are not always ways easily articulated (Henwood et al., 2018). In contrast, hydrogen advocates argue the similar performance of hydrogen to natural gas boilers may represent an opportunity to avert unnecessary disruption to consumer expectations and behaviours (EUA, 2021). Studies of hydrogen perceptions have however noted potential disruptions arising from the colour, odour and intensity of cooking flames in food preparation (Scott and Powells, 2020), and cultural associations with notions of combustibility and radioactivity (Flynn et al., 2013; Sherry-Brennan et al., 2010). While disruption in cooking practices would also be experienced in electric heating pathways, associations with radioactivity may be more problematic, disrupting perceptions of home as a safe and secure environment.

Despite the relatively recent emergence of hydrogen in heating policy discourse, there thus appears sufficient evidence in the literature to question the claim that hydrogen represents a less disruptive option for consumers. The remainder of this article details an empirical study which aims to identify the extent to which hydrogen is perceived as a less disruptive pathway in practice.

## 3. Methods

The research reported on below is the outcome of exploratory qualitative research conducted in October 2022. The study aimed to capture perceptions of heat decarbonisation in the round, examining heat pumps, hydrogen, heat networks and hybrid heating systems as well as the upgrades to network infrastructure which might be required to support them. Due to the widespread unfamiliarity of the UK public with low-carbon heating solutions, a deliberative methodology was adopted (Burns and Flegal, 2015). Groups of 7–8 participants were convened to learn about and discuss the topic over a prolonged period-in this case a one-day workshop lasting approximately 7 hours. While the small numbers participating limits the extent to which findings can be generalised to the population level, the scope for information provision and dynamics of small group discussion allow perceptions to develop and evolve in a more naturalistic setting than the pre-determined confines of a questionnaire (Macnaghten, 2017; Malone et al., 2010). Furthermore, deliberative engagements have been noted for their capacity to 'open up' consideration of technical topics to consideration based on a wider range of ethical criteria, social priorities and lived experiences than is possible in more tightly framed quantitative processes (Cherry et al., 2022; Demski et al., 2015; Krzywoszynska et al., 2018). This is especially important in studying a topic such as heating disruptions, where it is not yet clear how change will be experienced in practice by publics at large.

Two groups were recruited in October 2022, all participants lived in similar semi-detached housing in the northern suburbs of Cardiff South Wales. Semi-detached homes comprise 25% of the Welsh housing stock, representing a kind of median between terraced (27.5%) and detached (22.1%) housing.[1] As such, semi-detached residents were considered to represent a 'typical' case (Flyvbjerg, 2006) for examining perceptions of heating disruption, with a common housing and geographical context forming a focal point of shared experience around which detailed discussions could emerge. The two groups were further stratified into owner occupiers (hereafter OO), and a separate group of rental tenants (hereafter, RT). The rationale for this was that while each group may face similar material disruptions from construction and installation work, their agency and exposure to costs differ significantly (Longhurst and Hargreaves, 2019; NEA, 2017). Participants were recruited by a professional market research company and offered a £100 honorarium to ensure a diversity of socio-demographic perspectives (see appendix 1) could be sourced.

Workshops began with discussion and drawing activities framing deliberations in the context of participants homes and community. Participants were then shown a short presentation on heat decarbonisation and asked to discuss factsheets depicting the broad array of cost, in-home and distribution network disruptions associated with different heating technologies. Afternoon discussions centred on different modes of governing heat decarbonisation and a personas task (Cherry et al., 2022), designed to elicit sympathetic reflection on how heat decarbonisation may impact the everyday lives of others. The aim of these tasks was to elicit informed deliberations over heating disruptions, while maintaining focus on the everyday lives and concerns of participants. Workshops were video and audio recorded. Data was then transcribed and coded thematically in Nvivo 12. The analysis reported in this paper drew specifically on discussions of factsheet materials and arising from the personas task during which disruptions surrounding hydrogen and electrification were discussed more fully. Discussions of heat networks and hybrid systems while relevant to the topic at hand, tended to be briefer in nature and consequently have been omitted from discussion below .[2]

While our purposive approach to recruitment caries significant benefits in capturing common contexts and experiences through which disruption might be perceived, the focus on a restricted geographic location and housing type necessarily limits the extent to which we can be sure findings will transfer to other contexts. While semi-detached housing of the type studied here represents a significant proportion of the UK housing stock, it does not comprise a majority and differences in property size, age and location may well impact perceptions of disruption arising from network upgrade and building retrofit. Reliance on a single housing type and location thus represents an important limitation. Findings and methodological refinements from this study will be deployed to an extended range of housing types and locations in 2023. The findings reported on below thus represent emergent themes arising in exploratory research, rather than a definitive account of all perceptions of disruption that may emerge across a wider range of housing types and locations. We feel their publication is still warranted, both on the basis of scientific rigor; publication of exploratory findings enables critique and refinement of subsequent research and analysis, and that our indicative findings carry worthwhile lessons for ongoing trials and policy debates surrounding hydrogen heating.

## 4. Exploratory findings

### 4.1. The pressing issue of cost

While the research did not aim to discuss cost in isolation from other factors, it was conducted during a cost-of-living crisis characterised by rising energy, food, and housing prices in the UK. The default energy price paid by domestic consumers increased from £1137 for an average household in January 2019, to £2500 in October 2022. A widely reported increase to £3549 had been narrowly averted the month before, following last-minute government intervention. Cost was thus prominent in the minds of all participants and formed the key evaluative criterion by which they interpreted different heating pathways. By contrast the need to decarbonise heating and convert or reinforce energy networks seemed a distant and unfamiliar problem. Indeed, for participants experiencing higher levels of housing or financial precarity, to be speaking about potentially costly interventions in the energy system felt unfair and unreasonable under current circumstances:

[1] Bungalows (11.5%) and flats (11%) represent a smaller proportion of the overall housing stock, with the latter less reliant on gas heating due to safety and planning regulation.

[2] More data collection is needed in before we can draw strong conclusions on the disruptions publics associate with hybrid heating and heat networks. Preliminary analysis of the data collected so far contains nothing to contradict the main findings of this paper.

> "…. *But again, fair, that feeling of fair […] we need to sort our short-term problems and then think about emissions because, you know, we've said a few times now, we're worrying more about our, our bank accounts than the emissions.*" (Alan PRS)

Concerns around cost broadly subdivided into two categories. Hydrogen boilers tended to be viewed positively for the relatively low upfront costs required, but worries emerged when participants learnt hydrogen would likely remain more expensive than either natural gas or electricity. This led to significant concerns emerging that hydrogen might become a default heating fuel for lower income households despite higher overall costs: "*yeah, the heat pump is obviously the rational decision but I don't think he has the money to do that*" (Jenny PRS). Under these circumstances, the introduction of hydrogen was seen as both minimising initial disruptions to household finances from the installation of new technologies and network infrastructures, but at the same time threatening a more permanent disruption to everyday living costs which already represent a significant source of pressure and anxiety.

Concerns over running costs led to a tendency among participants to express preferences for heat pumps over hydrogen heating. However, this was highly contingent on support being provided to meet upfront capital costs, and firm assurances that heat pumps would be the lower cost solution: "*It's down to the running costs […], you'd need to see the difference in money to really decide, because it might not be as much as what we think*" (Rhian, OO). Firm guarantees or assurances on costs were often viewed as essential information participants would need before considering any alternative heating technology and uncertainties over future costs were viewed with a degree of frustration by participants.

### 4.2. Normality and network upgrade

While cost formed an ever-present element in discussion throughout both workshops, the issue of network upgrade tended to fall into the background despite attention being drawn to them in factsheets and moderator led discussions. When discussion of network upgrades did emerge, it tended to focus on impacts on traffic, parking and access to the home: "*I don't often come into town because it's just too busy for me. I can't stand it. But the traffic coming in, you know, if you've got all of this going on as well, it's going to be carnage*" (Michelle, PRS). However, most participants in both groups expressed a grudging tolerance of street excavations as an unwelcome, albeit necessary element of contemporary life. Pointing to the routine nature of maintenance and upgrades for water, energy, and telecommunications networks, they felt disruption arising from electricity network upgrades would be insufficient to justify uptake of a more expensive heating fuel such as hydrogen:

> "*It's irritating, but I'd much rather my road be dug up than my prices go up. Because it's like, how quickly do you forget about roadworks? If you drove today, you probably don't remember any roadworks you seen on the way, really. But you'd remember your prices going up.*" (Megan, PRS)

It should be noted that willingness to tolerate such work was conditional on the understanding that ongoing network upgrades would not restrict vehicular or pedestrian access to residences for prolonged periods: "*How would wheelchair people go back, manage without, or parents with children in prams and things?[…] You'd be confined to the house …*" (Jean, OO). Such concerns were seen as particularly acute for families with young children and those with age or health related mobility restrictions, for whom ease of access was deemed particularly important.

On occasions where network upgrades were deemed more problematic, this was in relation to service cables traversing boundaries between public and private property. In most cases, such boundary spaces were deemed primarily functional requiring little more than continued access. However two participants had invested considerable effort and care establishing mature gardens or ornamental driveways, and viewed disruption to these as unacceptable: "*It's not going to happen*" (Tom, OO). For these two, excavation for network upgrades did not represent a temporary disruption to access, instead it threatened far less acceptable disruptions to cared-for aspects of home. Underpinning these concerns was a belief that disruption to such spaces could or would not be repaired in the course of standard utility works: "*they wouldn't be doing it as, as nice as it was, they'd be patching it up, wouldn't they?*" (Gill, OO), remaining as permanent damage to the home.

While perceived disruptions from network upgrades might have operated to the benefit of hydrogen, this was undermined by the suggestion that this would require synchronised disconnections to convert the gas network. While shorter duration disconnections were seen as manageable, the proposal that connections to the gas network may be disrupted for up to a week were viewed as highly problematic: "*You wouldn't be without for a week. I mean, most situations you are without for a day or two, but a week […] It's frightening*" (Katressa, OO). Such concerns were particularly acute in relation to hygiene and childcare practices, such as bathing, laundry and home cooking:

> *"… I've got no hot water, so I wouldn't be able to bath the kids. I wouldn't be able to shower, I wouldn't be able to cook because my cooker is gas. So what would happen for that week? Where would I go? What do I do?"* (Michelle, PRS).

The above quote from Michelle is illustrative of the non-negotiable way in which participants, most often parents, viewed routine hygiene and care practices, which have been noted elsewhere as difficult to rupture (Hand et al., 2005; Sovacool et al., 2020), due to the social and cultural expectations underpinning them.

### 4.3. Disruptions to home

During initial discussions of heating upgrade and retrofit, discussions of in-home disruptions tended to be eclipsed by concerns over cost. However, the few participants drawn to hydrogen at this stage tended to be attracted by the low capital costs coupled with ease of installation as a direct replacement to a traditional gas boiler: "*If we can get that running cost down, we'd like that, because it's just […] like a day installation, and it's done*" (Gavin, OO). For the bulk of participants however, disruptions associated with installation work focussed on the occasional necessity of disruptive building work that comes with maintaining a home. There were however several circumstances where participants felt such disruptions would be undesirable. For example, Gill, an owner-occupier in her late 50's who had lived in the same home all her life, felt that after many years of renovations, she had reached a stage where further change was neither necessary nor desirable:

> "*If I moved tomorrow, I would 100% go for the, you know, the best option, because obviously I'd have the money to do it and the disruption wouldn't bother me. But actually staying where I am now, I would think no, I don't want to change.*" (Gill, OO)

Having reached a point in her life where moving home or substantial fabric changes were out of the question, less disruptive changes such as hydrogen or hybrid boilers appeared a more attractive solution despite the additional cost. Other participants noted households expecting to move, due to short-term tenancies, plans to downsize or purchase a larger home may also be reluctant to undergo substantial disruption. This was however seen as a minority concern, and even Gill shifted positions throughout the day, swayed by the difference in cost and a sense that fitting a heat pump may be a better option: "… *nobody likes disruption and with building and stuff, but I think as long as you, you're prepared for it, then it's a pain, but you're glad […] when it's finished, you know?*" (Gill, OO).

Other participants, while not necessarily drawn to hydrogen pointed to the "*unsightly*" (Jack, PRS) nature of heat pump fans, or the space required for the hot water tanks and, potentially, larger radiators needed to support their operation. Such concerns tended to sharpen as discussions moved away from factsheets to reflections on how heat pump retrofit might operate in the context of participants own homes or

impact on the lives of others: "*I'm just thinking logically, if he and his wife and two kids are in a smaller house and then you're potentially gonna take up more room, you feel like you're suffocating in a small house there's so many of you*" (Michelle, PRS). Concerns such as those voiced by Michelle and Jack were not expressed as a total rejection of heat pump technologies. Rather they suggested potential solutions such as the positioning of hot water tanks in attics, spare cupboards (if available), and the construction of ornamental covers to reduce the unsightly appearance of exterior fans. However, should such remedies prove impractical, the impact of heat pump retrofit was, at times, read as threatening permanent disruption to visual amenity and living space.

### 4.4. Mediated knowledge, experience and trust

Another pressing concern, emerging in both groups was the prior reputation of heat pumps. In each group, at least one participant arrived with some prior knowledge, raising questions over noise and, more significantly efficacy: "*some people were saying it's the best thing they've ever done and then there were other people saying that we spent all this money, and we're still blinking cold*" (Tom, OO). Mediated knowledge (Walls et al., 2004) about heat pumps, such as the reports from a radio documentary discussed in Tom's quote above, had a strong impact in shaping discussions of heat pump efficacy. Such reports at times intersected with direct experience of a previous generation of immersion heating and hot water tanks running cold, an uncomfortable experience some participants thought of as "*going backwards*" (Rhian, OO). Alongside such historical reminiscences, a concern emerged that a standardised heat pump installation may not account for the specific needs of households such as elderly residents desiring internal temperatures well over the average 20 °C. Similarly participants pointed to the need for flexibility to account for growing families, ageing and the onset of illnesses which may increase heating demands: "*they should really have a system in place which is, you know, as it is now with gas central heating, that does cover every eventuality doesn't it. You know, if you've got six people who … okay, costing more to run it but it can still cope with all those people*" (Jack, PRS).

Cutting across concerns over cost, network disruption and disruption to home was a more general concern over the integrity and competence of installers (Thomas et al., 2019). These arose in relation to all heating technologies examined and reflected beliefs that promised cost savings would not materialise; that infrastructure or retrofit work would be completed to a poor standard; or that shifts to decarbonise heat may generate a bandwagon effect where unqualified or unscrupulous installers caused damage to unsuspecting households. In some cases, such concerns were founded upon previous experience of local authority subsidised insulation retrofit: "*you have the work done and it's appalling … I've been there. You know, the last couple of years, it's just, it's, oh, it's horrible*" (Jean, OO). Safety concerns surrounding hydrogen did emerge at occasional intervals: "*Well it's just gas, isn't it? So it is quite scary*" (Rhian, OO) and one might have expected this to exacerbate mistrust in relation to hydrogen as a heating fuel. However, such concerns more often emerged in relation to more extensive heat pump retrofits, and in the case of hydrogen may have been mitigated by a belief that trusted installers or insurance providers such as British Gas would have fewer problems in pivoting to supply hydrogen ready technologies. Such a view would accord with previous hydrogen perception studies where participants reasoned that as a combustible gas, it would be subject to stringent safety testing and regulation (Scott and Powells, 2020).

## 5. Discussion

Across participants and groups, a pattern emerged in which cost consistently seemed to over-ride fears of disruption at both network and household scales. In part this may have been a product of the sample size and timing of workshops, but it finds support in previous surveys of heating preferences (BEIS, 2020; Williams et al., 2018). This operated to establish heat pumps as a more desirable technology for most participants to the detriment of hydrogen, due to the latter's higher running costs. Questions emerged over the fairness of heat decarbonisation pathways where those who are unable to afford heat pumps or are reliant on decisions of private landlords may be left dependent on more costly heating technologies.

As discussions proceeded, our efforts to frame heat decarbonisation within the context of homes and community impacts yielded a nuanced discussion of disruption. In particular, concerns arose around impacts on living space, and the sufficiency of heat pump technologies to meet the needs of changing biographies and family structures. Under such circumstances, future plans and contingencies intersected with the more durable fabric of homes to support desires for the kind of flexibility gas boilers have traditionally provided. Even here however, hydrogen did not emerge as entirely unproblematic. While perceptions of safety did not emerge as a major theme, concerns over the quality of work and duration of disconnections from the gas network during conversion sparked alarm among some participants. Cost remained the key evaluative criterion however, and significant reassurances over the long-term costs of hydrogen would be required before most of our participants would have supported its uptake as a heating fuel. Recent media reporting from the UK's first hydrogen village demonstrator suggest such assurances are already emerging as a key point of controversy (Lawson, 2022).

Families in small homes, older 'settled' households, or those expecting to move and thus unlikely to benefit from low running costs, tended to be discussed as those for whom hydrogen ready boilers may represent an opportunity. Likewise, concerns over heating sufficiency and desires to future proof heating systems to account for growing families, illness or infirmity may mitigate in favour of more flexible heating technologies. Such concerns may represent an opportunity for hybrid heating technologies where gaseous fuels such as hydrogen can provide occasional top-ups to heat pump systems. However, these biographical considerations are unlikely to cluster in the way that housing archetypes, hydrogen production infrastructure and industrial hydrogen users may. Thus while regional approaches to hydrogen conversion may prove efficient from a systems perspective, they are likely to include a broad swathe of homes for which electrification may be a better option, while excluding others who may benefit from a less construction intensive mode of heat decarbonisation.

Despite concern in the literature that the network aspect of heat decarbonisation may prove unduly disruptive for consumers, electricity network upgrades appeared in this study as a dog that didn't bark. Despite us providing information on network upgrades and a dedicated space to discuss them, these were not taken up as a topic for prolonged discussion. While a few participants did perceive potential for "*carnage*" in terms of traffic disruption and expressed concerns over access, the overwhelming majority saw such disruptions as temporary, manageable, and a reasonable trade-off to ensure heat decarbonisation at lower costs. Given the relatively intangible nature of energy networks (Roelich and Litman-Roventa, 2020), it is possible participants did not appreciate the scale of potential disruption the excavation of underground cables and installation of new substations may involve. Conversely it may be that the prior existence of substations and low-voltage distribution infrastructure in homes and communities make these appear less threatening than unevenly distributed high voltage lines. The lack of clarity on this question represents a potential limitation to this study, and one we intend to address in future workshops. Nevertheless, the relative lack of priority given to network upgrades reflects a broader pattern across participants where disruptions perceived as temporary such as construction work were seen as less important than the more permanent disruptions to heating bills, living space, or the boundaries where private property meets the network.

## 6. Conclusions

This article began from the premise that hydrogen has been presented by some as a less disruptive alternative to heat pumps for end users. Data collected to date suggests a more complex picture. While most participants did perceive the in-home disruptions associated with heat pumps to be disruptive, the temporary nature of such work and belief that disruptions may be mitigated, for example through positioning hot water tanks in attics. Conversely the suggestion that hydrogen conversion may, in some cases, involve prolonged disconnection from the gas network was viewed as highly disruptive. Should significant portions of the gas network be converted to hydrogen in the future, affected citizens are likely to require reassurance on the duration of any disconnection. Where prolonged disconnection is required additional mitigation such as temporary bathing and cooking facilities might be needed to allow families to continue to meet social expectations of cooking and hygiene.

The issue of cost, already the key factor in shaping heating replacement decisions (BEIS, 2020), was likely exacerbated by recent rises in energy bills. Put simply, any decarbonisation solution resulting in higher energy bills is likely to be perceived as posing an unacceptable disruption to already precarious household finances. This may pose a key challenge for hydrogen network conversion and assurances on cost are likely to be needed, extending well beyond the relatively short life of current pilot studies. This is not to say that heat pumps were viewed an unproblematic, with high upfront prices viewed as a significant barrier to uptake. Moreover, some participants feared hydrogen ready boilers may became the default option for renters. That heat pump technologies could be unaffordable for some raised significant concerns for distributive justice and with it, public acceptability (Thomas et al., 2020).

Our findings thus call into question gas sector incumbents' framing of heating electrification as a disruptive process for consumers to which widespread conversion of gas provision to hydrogen can be a solution (Lowes et al., 2020). Our deliberative approach to 'opening up' (Pidgeon et al., 2014) framings of disruption illustrates the partial nature of hydrogen advocate's account of disruption which omits disconnection and financial disruptions which mattered as much to our participants than construction work in the home or on energy networks. An emphasis on construction related disruptions could be read as an exercise of discursive power, legitimising continued reliance on fossil fuel resources, infrastructure and technologies, while closing down or delaying alternate sociotechnical pathways (Friends of the Earth, 2022; Stirling, 2008). This strategy may have delayed policy action on electrification and heat networks, and it may come with unintended consequences if real-world hydrogen heating deployments are experienced as financially disruptive by affected communities. Hydrogen is already a contentious option, particularly when derived from fossil fuels (Friends of the Earth, 2022). There is a risk that disruption in the space heating sector may create negative associations that carry over into hydrogen fuel switching in other sectors such as heavy transport and industrial process heat where fewer decarbonisation options are available.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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## Appendix 1

*Participant demographics*

| Gender: | | Age: | | Estimated Social Grade: | | Tenancy status: | |
|---|---|---|---|---|---|---|---|
| Men | 6 | 20–29 | 5 | AB | 2 | Private Rented | 4 |
| Women | 9 | 30–39 | 2 | C1 | 3 | Socially Rented | 3 |
| | | 40–49 | 3 | C2 | 3 | Owner Occupier | 8 |
| | | 50–59 | 2 | DE | 4 | | |
| | | 60–69 | 2 | | | | |

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