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A relational approach to characterizing householder perceptions of disruption in heat transitions

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Heat decarbonization threatens substantial disruptions in temperate countries. However, the concept of disruption carries diverse meanings, potentially relating to cost, material space and everyday heating practices. Here, using interpretive risk theory, this article elucidates a relational understanding of how disruption is experienced and takes on meaning in everyday life. We deploy this framework to examine perceptions of four low-carbon heating technologies—heat pumps, hydrogen, hybrid heating and heat networks—alongside associated upgrades to distribution network infrastructure. Drawing on data from six, 1-day workshops representing a diversity of geographic and housing contexts across the United Kingdom, we address how existing relationships shape hopes, fears and expectations for heat decarbonization. Our findings help clarify the role of affective relationships, feelings of precarity, security and pressure in distinguishing material inconveniences from more fundamental disruptions to valued ways of life, and may be particularly relevant in other gas-dependent countries and regions.

Decarbonization entails substantial disruptions for states, citizens and corporate entities, resistance to which may pose a risk to low-carbon transitions[1]. This may be especially true as transitions proceed beyond electricity generation to areas such as heating, food or transport, where changes expand into spheres that are often considered the domain of private preference and everyday life[2]. However, disruption remains understudied in energy research, which often appears under the rubric of technology or systems transitions. While a systemic focus is beneficial in identifying value trade-offs, justice implications and the potential for unintended consequences[3], it comes at the expense of attention to the everyday relationships and expectations that may be impacted by decarbonization processes[4]. Attention to social relations is needed to better understand and differentiate between changes that may be inconvenient but more or less easily adapted to, and more extreme disruptions, which pose fundamental challenges to social acceptability.

In the field of domestic heating, transformation of established technologies, practices and associated network infrastructures are necessary to achieve internationally agreed climate goals[5]. Internationally, heat decarbonization policies often rely on consumer choice and appear insufficient to meet climate objectives[6]. While publics in many temperate climates profess to value environmental protection in future heating systems[7], knowledge of low-carbon heating options is low and many may be unaware of the contribution that gas boilers make to climate change[8]. Pro-environmental attitudes are thus yet to translate into low-carbon heating uptake in most gas-dependent countries[9]. One reason for such hesitancy may be disruption, which has been raised in policy discourse as a challenge to the acceptability of heat transitions[10]. Disruptions have been primarily framed in material terms such as heightened costs, changes to building fabric and heating practices[11,12]. Road excavations and disconnections needed to reinforce electricity distribution grids or install heat networks have also been raised as posing disruptions to communities[8,13]. The scale of these material changes may be particularly acute in temperate countries locked into mature gas networks such as the United Kingdom, the Netherlands and the eastern United States[14].

Our aim in this article is to expand on material conceptions of disruption to better capture why it is that specific material changes

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Table 1 | Breakdown of participants by group

Group	Housing type and year built	Tenure	Gender split	Age bracket	Estimated social grade	Heating type
Llanishen, Cardiff (CF-OO)	Semi-detached 1945–1989=8	Owner occupied=8	Female=5 Male=3	18–29=1 30–39=0 40–49=3 50–59=2 60–69=2	A/B=2 C1=1 C2=2 D/E=3	Natural gas=8
Llanishen, Cardiff (CF-SPR)	Semi-detached 1945–1989=7	Private rented=4 Social rented=3	Female=4 Male=3	18–29=4 30–39=2 40–49=0 50–59=0 60–80=1	A/B=0 C1=2 C2=2 D/E=3	Natural gas=7 Electric resistive=1
Hardwicke, Gloucester (GL-D)	Detached 1990–2020=8	Owner occupied=7 Private rented=1	Female=5 Male=3	18–29 = 30–39=1 40–49=3 50–59=3 60–80=1	A/B=3 C1=2 C2=2 D/E=1	Natural gas=8
Toxteth, Liverpool (LV-T)	Terraced Pre-1930=9	Owner occupied=2 Private rented=6 Social rented=1	Female=5 Male=4	18–29=2 30–39=2 40–49=2 50–59=1 60–80=2	A/B=0 C1=2 C2=3 D/E=4	Natural gas=9
Crosby, Liverpool (LV-C)	Terraced Pre-1930=5 Semi-detached Pre-1930=4	Owner occupied=5 Private rented=3 Social rented=1	Female=4 Male=5	18–29=0 30–39=2 40–49=3 50–59=2 60–80=2	A/B=2 C1=4 C2=1 D/E=2	Natural gas=8 Electric resistive=1
Scottish Borders (SB-OG)	Detached 1800s–2020=6 Semi-detached 1940–1989=1 Tenement 1945–1989=2	Owner occupied=3 Private rented=2 Social rented=3	Female=4 Male=4	18–29=1 30–39=2 40–49=1 50–59=1 60–69=2	A/B=1 C1=2 C2=3 D/E=2	Electric resistive=4 Oil boiler=2 Wood stove=1

A/B: higher and intermediate managerial, administrative and professional occupations; C1: supervisory, clerical, and junior managerial, administrative and professional occupations; C2: skilled manual occupations; DE: semi-skilled and unskilled manual occupations, unemployed and lowest grade occupations.

matter to publics and distinguish between changes that might be considered tolerable inconveniences, from more fundamental disruptions to everyday life. We develop a relational approach[15] that theorizes disruption as a psychosocial phenomenon. By psychosocial, we refer to forms of sense-making that account for the cultural discourses, values or identities circulating in a particular social group, as well as the relationships, feelings and experiences that give psychological meaning to those discourses at a personal level[16]. We elucidate this approach through analysis of qualitative data collected during 6 deliberative workshops on heating transitions conducted with members of the public (total $n = 49$), stratified to reflect diverse relationships to heat retrofit based on property age, location and housing tenure (Methods and Table 1). Discussions represented four key technology and infrastructure pathways for UK heat decarbonization[11], covering heat pumps, hydrogen, hybrid systems and heat networks. Our findings clarify how changes to heating technologies and networks may impinge on an array of relationships, including care for family, cultural expectations of home, and positioning in wider economies of finance and housing, the precarity of which can render heat decarbonization not only materially but also culturally and psychologically disruptive.

A relational approach to disruption

When disruption is discussed in transition studies, it is often under the rubric of disruptive innovation, whereby technologies emerging from niche applications overturn the value metrics upon which incumbent firms' success depends[17]. At systems scales, disruption is not confined to a single product; it reshapes governance and regulation, actors, ownership structures, and the business models through which technologies and services are delivered[18]. Within such models, disruption is akin to creative destruction; to achieve step-change reductions in carbon emissions, some disruption to incumbent business models and socio-technical regimes is to be encouraged[19]. While useful for considering the productive potentialities of disruption, such models may be less appropriate when considering impacts on diverse and sometimes marginalized publics, for whom change may be experienced in negative terms[20].

In everyday speech, disruption carries a negative valence, implying deviation from previously anticipated trajectories; 'we apologize for the disruption to your journey'. In the sociology of health, biographical disruption refers to interruptions to personally and socially expected life course trajectories experienced as a result of chronic illness[21]. Viewed thusly, disruption is less about creative destruction than relationships between personal, lived experiences and cultural resources such as social norms, values and identities, which shape feelings and interpretations of material changes to everyday life. This view of disruption is similar to relational theories of risk[15,22], wherein perceptions of the threat posed by a given change are shaped by our relationships to other culturally and subjectively valued objects that change may impinge upon (Fig. 1). Rather than anticipating the scale of material changes that heat decarbonization may bring, understanding disruption in relational terms pays attention to expectations around differently framed problems and solutions[23], and to how discourse and lived experience of specific contexts shape feelings towards new heating pathways[24].

Interpretive risk analysis often turns on the study of heterogeneous narratives through which individuals and groups make sense of material change in light of past experiences, shifting cultural values, identities, and economic and social experiences[23]. Initial interpretations involve social-cognitive processing and situated appraisals, identifying sequences of events and consequences and assigning them importance based on the norms and values into which we have been

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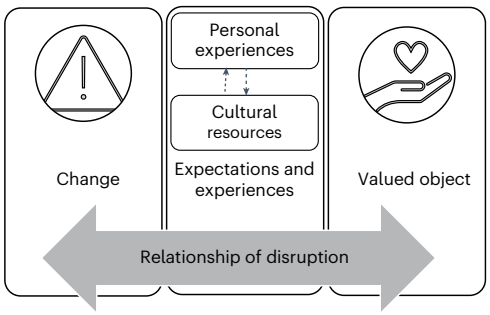


Fig. 1 | Conceptual framework for a psychosocial approach to disruption. Disruption is experienced relationally when expectations of stability invested in a valued object are threatened with change. The values disrupted may derive from our personal experiences of or relationship to that object, the cultural resources such as discourse and social identities with which it is associated, or some combination of the two. The concept is derived from Boholm and Corvellec's relational theory of risk[15].

socialized. Affective and emotional experiences, feelings generated through our interactions with society, culture and our material environments are also fundamentally important in narrative sense-making, shaping how we respond to proposed changes in circumstance and communicate such feelings to others[16,25]. Disruption in this view comes into focus through what Archer[26] refers to as the 'internal conversation', a reflexive movement between a rational deliberative mode of thought, and affective or emotional responses comprising feelings and visceral bodily responses, which are less easily subjected to calculation and trade-off but can often alert us to the people, objects and relationships that matter most. Through this conversation, humans anticipate what they can achieve within their material and cultural context, conceive and adjust projects that they hope will contribute to an affectively, emotionally or socially rewarding way of life[27].

The bulk of heating perceptions research (for an overview, see ref. 28) operates at the deliberative level, drawing attention to the importance of cost, comfort, construction work and material impacts on living space[7,8,29,30]. Such studies deal with material factors and bodily experiences, but do not adopt a relational approach. Rather, they treat these variables as elements of cognition and perception, translating material relations to heating into preferences and judgements from which individual actors anticipate the potential outcomes of installing different systems. This offers only limited insight into the culturally and emotionally important projects and practices that may resist or be disrupted by uptake of low-carbon heating technologies. A good example is the finding in such research of a need for trusted installers and independent advice on retrofit options and financing. This can be interpreted narrowly as a cognitive evaluation of the conditions underlying our degrees of perceived 'trust'[29]. Alternatively, in relational terms, this finding points to a plethora of social relations necessary to give individuals confidence in low-carbon heat retrofit[31,32]. Such work acknowledges the strength of existing relationships, financial constraints, and uncertainty over the performance of unfamiliar technologies, external actors and routines as social constraints on decision-making rather than the properties of technologies or individuals' psychology.

Relational approaches are not new to energy social science[33] and are especially prevalent in practice theoretical approaches to heating retrofit where relationships between new technologies, regulatory regimes, socio-cultural expectations and identities have all been noted as shaping enrolment in heating routines[34,35]. While such work has much to offer, it often relies on data gathered from trials and early adopter groups who have already decided to participate in heating retrofit[36]. While this affords a clear focus on the practical changes involved in switching heating systems, it overlooks the majority who are not yet engaged with heating retrofit, or the sizable proportion of trial volunteers who opt out of fully funded retrofit schemes citing concerns over disruption[37]. As such, they offer only partial insight into the cognitive domain of anticipation and the emotionally and affectively tinged valuations that come into play with non-routine decision-making. Under such circumstances, we argue that a psychosocial, relational approach offers an appropriate middle ground between a view of individual cognition as pre-eminent and attendance to feelings and cultural practices that shape our feelings towards potential change.

Distinguishing inconvenience from disruption

Across workshops, participants tended to view network upgrades or temporary service disruption as the least problematic aspect of heat decarbonization, reflecting cultural understandings of maintenance and upgrade as common and necessary aspects of modern life—signalling for them inconvenience rather than any fundamental challenge to relationships or life projects. Beyond the temporary impacts of construction, in-home changes were seen as threatening a broader range of meanings, aspirations and relationships woven into the fabric of participants' everyday lives, while cultural meanings and identities associated with place also had a strong impact in shaping perceived disruption in some groups[38,39]. While the material impacts of construction work were often dismissed as inconveniences, challenges to relational ties were seen carrying far greater potential for disruption.

Regarding infrastructure upgrade, while some participants expressed concern over traffic 'carnage' and car parking difficulties during excavations for electricity network upgrade or heat network installation, most viewed this form of work in fatalistic terms as an inconvenient but inevitable aspect of modern life, and something that could be adapted to. Some expressed an expectation that sufficient notice would be given to allow adaptation, while others expressed a desire for better coordination between local authorities and utilities to reduce the frequency of excavations. While such statements reveal a degree of frustration over a patchwork response to infrastructure maintenance that was perceived as typifying the approach of UK authorities, they do not question the underlying project of network upgrade.

Temporary disconnections during network conversion or reinforcement were seen in similar terms. However, pre-existing relationships of care for young children or mobility-impaired people could complicate these inconveniences, turning them into something more disruptive. Such relationships came into play as participants discussed already stressful school and commuting regimes, or difficulties accessing homes with prams and wheelchairs. Under such circumstances, network upgrade was seen as interfering with socio-cultural expectations of mobility, hygiene and caregiving[35]. Such concerns became especially acute when discussing disconnections lasting up to a week during hydrogen conversion, where lack of access was seen as posing unacceptable disruptions to bathing and food preparation routines, which were seen as prerequisites for good parenting. Suggestions for mitigation ranged from early warning of traffic works and measures to ensure continued access to residences, to the provision of temporary accommodation, meals, cooking or bathing facilities. While some participants expected that government or utility companies would provide mitigation, others expressed extreme scepticism that this would be the case.

Some aspects of in-home upgrade were seen in similar terms to network upgrades; in particular, temporary construction work for retrofit was at times compared with the periodic maintenance and home improvement projects that punctuate the biographies of many homeowners[40]. Such material changes were often discussed as temporarily stressful but necessary for greater enjoyment or amenity to be achieved. However, concerns were raised for vulnerable households unable to adapt to or avoid disruption during construction work. Reflecting on her own experience caring for her elderly mother with dementia, Yasmine (Liverpool-Terraced [LV-T]) noted how frightening

the prospect of noise, dust and unfamiliar workmen entering the home could be: "It's gonna kill them, half of the older generation […], they're not gonna be able to handle that".

Participants in the Scottish Borders expressed strong rural identities in some respects, but they did not construct heat pumps or insulation enhancements as a particularly egregious disruption to this identity, potentially owing to the low-density historically varied pattern of housebuilding in the area. In Liverpool, however, numerous participants expressed pride and strong class-based identifications with the city's densely packed Victorian terraced streets, both for their historic character and aesthetic, but also as "a symbol of working class communities" (Andrew, LV-T). Not only was the physical environment of such streets seen as posing a challenge for siting heat pumps and new substation infrastructure but also alterations to such properties were seen as threatening a symbolic disruption to cherished place and class heritage, bound up with terraced living.

Key in the narration of such identities were stories of care for and restoration of historic features such as floor mosaics or cast-iron radiators that several participants had invested substantial time, effort and money in restoring and caring for. Such effortful material investments[41] in Liverpool's older properties added an embodied relationship to the wider cultural values associated with such homes. Removing period features to install new service cables, fans, insulation or radiators was thus seen as disrupting both the historic and class identities bound up in Liverpool's housing stock but also investments of time, effort and care made to help preserve these symbolic objects.

Elsewhere, we found similar accounts of effortful investment, in the renovation of loft spaces to accommodate growing families, the establishment of new front gardens or installation of an ornamental driveway. While linked to different values such as the cultivation of tranquillity, smartness and automobility, or expectations of family life, these also involved accounts of physical and mental effort expended towards specific life goals. When such investments were present, disruption in the form of excavation, solid-wall insulation or loss of space for hot water tanks was seen as threatening not only the practical use or cultural meaning but also the anticipated outcomes of hard-won life projects. Even among participants yet to undertake such improvements, the mental effort expended in planning and anticipating future projects that they hoped to undertake led to feelings of disruption upon hearing about heat pump space requirements.

Precarity and security shape feelings towards disruption

Cost has frequently emerged as an issue in studies of heating perceptions, either as the primary criteria upon which decisions are based, or as a constraint sidestepped in subsidized trials[36]. Reflecting this, deliberations over potential costs formed a key focal point for discussion in all workshops. However, the meanings of cost comparisons were constantly in flux, informed by feelings of relative security or precarity[42] arising from not only income but also relationships to landlords, employers and welfare services. It was these feelings of precarity and security that ultimately shaped whether heat decarbonization was interpreted as a sound investment or as threatening unacceptable disruptions to household finances.

Across workshops, cost comparisons formed a default metric for comparing between different options. The ability to weigh up trade-offs between capital cost, operating cost, appliance lifetime and (less frequently) environmental impacts was often seen as essential for making the most "rational decision" (Jenny, Cardiff-Social and Private Rented [CF-SPR]). Concerns over affordability and frustration at uncertain cost estimates that hindered rational cognitive evaluation thus made the experience of comparing different heating options stressful for many participants. While heat pumps were seen as offering a temporary form of financial disruption owing to higher capital costs, hydrogen was seen as potentially more disruptive owing to higher operating costs over the long term. Mirroring concerns raised elsewhere[43], heat networks were seen not only as potentially more affordable than individualized heating solutions but also as creating opportunities for monopolistic power to threaten further financial disruptions in the future. Furthermore, recent instability in fossil fuel pricing gave rise to a discourse in which geopolitical reliance on natural gas or imports for hydrogen production risked laying foundations for future disruptions to energy affordability.

By contrast, heat pumps and, to a lesser extent, heat networks often benefited from an expectation that government or local authorities would cover the costs of retrofit work, allowing for an element of socialization as well as spreading costs over a longer period than a commercial loan arrangement. Cultural expectations of private housing as a sensitive domain to some extent immune from the changing whims of government[10,44] brought an expectation that any pressure to adopt more costly technologies should be compensated: "I'd say the government [should pay for retrofit] because they're forcing it upon us" (Ciara, LV-T).

The one exception to this rule were detached homeowners in Gloucester and the Scottish Borders. Noting their own relative financial security, these participants were more prepared to consider the argument that households such as theirs might need to contribute towards housing retrofit. While seeing an outright ban on gas boilers or withdrawal of the gas network as unduly coercive, this group was prepared to view changes to energy performance regulations, property tax and even energy bills as an acceptable means of incentivizing households to engage in retrofit, discussing them in terms of already familiar house purchasing and investment practices. While much of this discussion mirrored policy debates constructing home purchasing, remortgaging and renovation as 'trigger points' for heat retrofit[45], Gloucester participants were notable as the only group to whom a narrative of investment to future proof against future regulation was meaningful, probably owing to their greater financial security.

In the private rented sector, much policy discussion has focused on split incentives between landlords who might pay for retrofit measures and tenants who may benefit through their bills[46]. By contrast, lack of protections for tenants emerged as a far more prominent concern across all workshops, regardless of participants' tenure status. This discourse was most pronounced in our group of Cardiff renters where experiences of insecure tenure, rapidly rising living and rental costs, and landlord non-compliance with basic repairs and maintenance led to pronounced feelings of precarity in the face of heat decarbonization. In most cases, such participants feared 'coerced consumption'[47] of heat pumps, whereby landlord decisions to install low-carbon technologies would lead to increased rents and bills, leaving tenants with no recourse but to pay up or move on. Conversely, some participants raised the prospect of widening inequality should landlords opt for cheaper to install hydrogen boilers, while homeowners could invest in heat pumps as a cheaper option in the long term.

Financial and housing precarity also intersected with proposed changes to building fabric in ways that rendered loss of space for heat pumps and associated thermal storage equipment more problematic:

> "But what about if there isn't room in the house? Because let's not forget, a lot of families now, like [other participant], they're all cramming into smaller houses 'cause they can't afford bigger houses. So adding in more equipment, what about if there is no room for that?" (Michelle, CF-SPR)

For Michelle, already coping with insecure tenure and the struggle to fit a growing family into a property that she could afford, the idea of finding space for a hot water tank represented a further disruption to already unstable housing relations and normative cultural expectations of adequate, affordable and secure family housing[42,44]. The potential financial and spatial disruptions associated with heat decarbonization made it almost unthinkable for Cardiff tenants who collectively

declined to express a final preference between options that they felt could only offer further disruption and precarity.

Choice pressures and fatigue

Policy measures seen as enforcing conversion to low-carbon heating, for example, via conversion of natural gas networks to hydrogen, or disincentives for homes remaining on carbon-intensive fuel supplies were not only seen as disrupting relationships to home and household finances. Coerced changes were also seen as disrupting expectations of autonomy and choice, a core value in public deliberations over energy systems change[3,7]. Furthermore, many participants expressed discomfort at the expectation that heat decarbonization may require them to make decisions relating to uncertain, costly and potentially disruptive changes to their homes. Citing precarious financial relationships, and the competing pressures and stress of existing responsibilities, some questioned whether individualized decision-making over retrofit was conductive to individual and collective well-being.

Concerns over choice often manifested not only in scepticism towards heat networks as fostering local authority monopolies but also in cynicism towards policy instability with frequent reference to multiple changes in the UK government between 2016 and 2023. Concerns about perceived dishonesty and incompetence also appeared in the sphere of energy where nuclear, renewable subsidies and fracking were all noted as seemingly abandoned after initial spates of government enthusiasm. In Liverpool, discussion of a proposed hydrogen heating trial in the nearby village of Whitby was met with alarm that powerful interests would 'push hydrogen' on the city: "We're being shafted again. Because it's an expensive choice. Not a choice, should I say" (Katie, Liverpool-Crosby [LV-C]). By contrast, electrification was often seen as more analogous to fibre-optic broadband, where citizens gain service options once new infrastructure is installed, but are not obliged to connect.

However, as noted elsewhere[31], desire for choice encountered hard limits when it came to the installation of costly and materially complex changes to building fabric. These raised a plethora of concerns over how citizens might make good decisions over complex and unfamiliar heating systems, locate trustworthy installers and find good value funding solutions. Independent, 'one stop shop' style advice services, individually tailored systems and finance packages, and public information campaigns were seen by all participants as prerequisites for having confidence in unfamiliar heating technologies. The ability for households to 'do your own research' and make judgements departing from official advice was often seen as important to ensure that such services remained honest and value for money. Nonetheless, the availability of a trustworthy and easily identifiable default provider in each community was seen as necessary for householders beginning the process of retrofit and peace of mind for those lacking the capacity to navigate complex retrofit packages.

Availability of a default option was not seen solely as a solution for vulnerable households. Across several groups, a combination of perceived coercion to engage in retrofit and the costs and complexity of doing so was seen as intersecting with other pressures in ways that could disrupt citizens' capacity to live their lives as they might otherwise wish: "I can't even go to McDonald's anymore, because I feel like I've gotta get a vegan burger [laughter]" (Andy, LV-C). In some instances, this manifested in concerns over being made to feel guilty about heating or making the wrong retrofit choice. In others, it took the form of frustrations over the time and complexity likely to be involved in considering and selecting appropriate retrofit measures:

> "I'm busy, I don't need, I don't wanna go to a one stop shop [for retrofit advice], I'm bringing up two children and working full time, thank you very much. If someone just tells me that they're gonna do it and they're gonna make it cheaper than if I did it on my own […] great, go and do it." (Lucy, Gloucester-Detached [GL-D])

While shaped by the high financial and material disruptions that could accompany incorrect retrofit choices, such pressures also point to the precarious relationalities of contemporary life. This comprised not only concerns over social judgement over emergent pro-environmental norms[48] but also a plethora of obligations and psychological investments regarding work, care and family life that participants were already balancing[41,49]. When combined with concerns over being forced by changing network availability or disincentives for fossil fuel use, the fatigue of existing expectations and commitments manifested in a degree of exasperation at the additional intellectual and emotional burdens that retrofit may place on the well-being of already overburdened households.

Mirroring earlier discussions of heat pump costs, frustrations over such retrofit burdens were often resolved through appeals to government and via the mechanism of a one-stop-shop advice service as a default option to take the stress out of making choices. Underlying such hopes however was a feeling that selecting between low-carbon heating ought not to be a risky process that leaves some households worse off, victims of questionable tradesmen or opaque energy or appliance markets. Such concerns took on a political dimension in the Liverpool, a city with a long tradition of left-wing politics and trade union activism often at odds with nationally elected Conservative governments. Here explicitly politicized place and class-based identifications, "its them and us" (Linda, LV-C), led to sustained critiques of privatization and the UK's history of electing Conservative governments. The two Liverpool groups were unique in identifying heat networks as a preferred option, both as a means of insulating the city from the disruptions and dislocations of privatized heating provision, and to express feelings of local solidarity and collective identity, justifying potentially inconvenient network upgrades:

> "There's, there's roadworks everywhere isn't there, we've, we've got it anyway, we've, we've learnt to live with it. So if we're gonna get something that benefits as an individual and as a community… and in your pocket…." (Lee, LV-C)

Conclusion

Our relational, psychosocial account of disruption offers numerous benefits for considering heat decarbonization and network upgrades. First, it has enabled us to add greater depth of understanding to policymakers' concerns that street excavations and the establishment of additional energy network infrastructure may pose an unacceptable disruption to publics. While the observation that network upgrade work is more of an inconvenience than a major psychosocial disruption may appear obvious, material and economic disruptions caused by network upgrades have been a growing point of discussion in the policy and grey literatures surrounding electrification and heat decarbonization, which has yet to receive social scientific scrutiny[12,13]. Our analysis shows that feelings of stress and caring practices tied to parenting and sympathy for vulnerable others do raise concerns over prolonged network disconnections, which would require mitigation were network upgrade to accelerate. However, it also shows that past familiarity with network maintenance, cultural understandings of its importance to modern life and capacity to open up new choices and services mean that most are likely to tolerate disruptions arising from network upgrade. While a small number of participants did raise queries over the appearance, safety or noise that might be associated with new electricity network infrastructure, this was never cited as a reason not to proceed with heat decarbonization.

Second, in providing a forum for participants to narrate and explore what are normally internal conversations over past and future domestic projects and retrofit interventions, our approach expands on understanding of how relationality shapes energy demand[33], highlighting the psychosocial processes that come into play when citizens consider non-routine practices such as heating system replacement.

While our work reaffirms the importance of building fabric and heating systems as a means of reproducing culturally valued identities, care and hygiene practices[35], it also identifies the importance of subjective intentions, plans and aspirations that practice theoretical literatures often overlook. Furthermore, it illustrates the complex ways in which perceptions of disruption combine more-or-less rational cognitive processes, weighing costs, environmental implications and trust in potential providers, with considerations of identity, feelings of stress and precarity, and emotional attachments to home.

More specifically, our analysis illustrates how biographically and culturally patterned homemaking projects embed affective relationships and expectations in the fabric of domestic spaces, which, in turn, shape how proposed retrofit measures are evaluated. Sometimes, these relationships may follow common trajectories, for example, the expectation that an adequate family home requires space to grow, or that after multiple rounds of home renovation, a point may be reached where older people no longer anticipate or desire to make substantial fabric changes and may lack the capacity to absorb its disruption. In other instances, relationships may be more idiosyncratic, such as care for an old radiator or even a neatly laid driveway, which nevertheless embodies previous effort, aspirations for improvement or expectations of preservation. Close attention and sensitivity to such relations may mark the difference between heat decarbonization success stories and tales of disrupted family ambitions, lost connections to history, or damage to the hard work and identities invested in homes and everyday life.

Third, a relational understanding also reveals the logics underpinning why material changes to household finances and fabrics matter. Such changes are not solely focal points of mental calculation or elements in difficult-to-break practices. Rather, they are embedded in overlapping and wide-ranging structures of cultural and economic relations, encompassing normative understandings of what constitutes adequate housing that guide subjective expectations. Across groups, experiences of precarity prompted by geopolitically driven spikes in gas prices often led to the identification of hydrogen as a 'non-solution'[3], further entrenching reliance on costly fossil resources. In some regards, such findings may be read as reiterating well-worn discussions over the importance of costs and spatial constraints in shaping decision-making over heating uptake or support for retrofit policy[7]. However, it also points to the underlying structures of precarity[42] that can render changing cost structures especially problematic for some. Publics do not expect to bear these intellectual and financial burdens alone, and require safety nets, the provision of which may fall under the jurisdiction of housing or welfare rather than energy policy[50].

Feelings of precarity are highly situated. For those with secure housing and a financial cushion to fall back on, retrofit costs may appear more akin to an inconvenience than a fundamental disruption to valued ways of life. Our analysis also illustrates alternative sources of security such as place and class-based identifications that under some circumstances may give confidence in more collective forms of heat provisioning. While recognizing the material disruptions that such changes may entail, participants discussing heat decarbonization from a position of security were able to articulate positive benefits for themselves, the environment and their community.

Finally, focusing on the relational, psychosocial elements of heating disruptions allows us to see how retrofit processes are not only costly and materially complex but also potentially fatiguing in the context of strained finances, family life, work and a plethora of other cultural expectations around homemaking and pro-environmental consumption. At times, fatigue gave way to resentment over a perceived imposition of additional heating-related worries and decisions, which occasionally intersected with other instances of environmental 'guilt' such as over dietary choices. At stake in such instances was less concern over a single disruptive event, but rather a perception that environmental policy-making may thrust a host of new uncertain decisions and responsibilities onto households already struggling to manage.

This is not to say that participants rejected heat decarbonization as a legitimate goal or problem framing. As with other studies and deliberative engagements[7,8], we found that participants were open to the view that fossil fuel use required urgent transformation, even though they were not initially poised to see heat decarbonization as a priority. Tensions between the general, normative form of evaluation and feelings of fatigue and stress tended to be resolved through appeals to independent advice services and expectations that the government should pay. These appeals could be regarded as non-resolutions reflecting how family life in precarious times seriously limits the intellectual and emotional energy that some have to engage in pro-environmental consumption and decision-making. Yet this situation could alter near term if policy gave less emphasis to the decision-making of individual consumers and established ways of supporting citizens financially, intellectually and emotionally so they can live well while engaging in heat retrofit and other low-carbon lifestyle projects.

Methods

Case selection and recruitment

Case selection was purposive, aiming to reflect diverse relationships to place, building fabric, energy networks and housing markets (Table 1). Property age and location are important proxies differentiating ease of low-carbon heating retrofit, both in terms of the volume of changes required to building fabric[51] and the necessary network infrastructure upgrades[13]. Yet it is also necessary to account for the meanings and values that residents endow in homes and communities that might be placed at risk by material changes arising from heating retrofit and network upgrade[15,52]. Such values may include not only social understandings of home as spaces in which family life and caregiving unfold, and associations with safety and stability, but also ethical beliefs, practices and identifications bound up with living in a particular kind of place and home[38,39,41,53].

Attending to these relational contexts is important for understanding how publics might respond to the specific disruptions to homes and energy networks that different pathways for heat decarbonization might entail. Such relationships are further complicated by positioning in housing markets and expectations of financial security bound up with housing tenure, borrowing and financial investment[36,54]. While attention has been paid to experiences of owner occupiers and residents in the more secure social rented sector[24,36], private sector tenants often find themselves facing insecurity of tenure, high housing costs and low-quality housing[42,50]. We thus sought specific representation of this more marginal group to explore how heat transitions may proceed in a more just manner[20].

Stratifying recruitment according to location, housing age and tenure helped ensure that each group reflected a common repertoire of knowledge and experience, easing the flow of interactions and allowing for more nuanced deliberations of how proposed policies or technologies may translate into different relational contexts[55,56]. Reflecting the substantial proportion of the United Kingdom's easy-to-insulate housing stock, two groups were recruited in Llanishen, Cardiff, comprising residents of semi-detached housing built between 1945 and 1989 (ref. 57). Groups were stratified into owner occupiers (CF-OO) and tenants in the private and social rented sectors (CF-PSR). A suburban area of Gloucester (GL-D) was selected for its prevalence of detached housing, built after 1990; such homes have limited need for insulation retrofit. Sitting atop relatively modern electricity networks, such homes may still experience early network disruption owing to a prevalence of white-collar professionals, a group disproportionately likely to install heat pumps[58]. The two Liverpool groups were selected to represent older hard-to-insulate solid-wall properties built before 1918 (ref. 51). Participants were recruited in areas around Toxteth (LV-T) and Crosby (LV-C), with the former being a diverse but low-income urban

neighbourhood characterized by terraced housing, and the latter being a more upwardly mobile suburb comprising a greater mix of terraced and semi-detached housing. The area surrounding Hawick, Scottish Borders (SB-OG), was selected as a rural region with limited access to the gas grid. Off-gas regions are an early target for heat decarbonization owing to their reliance on costly and polluting oil central heating and inefficient resistive electric heating. Participants in this group were recruited to reflect diverse housing and socio-demographic backgrounds.

Reflecting the diversity within these relatively homogeneous categories, each group was recruited to ensure even gender representation and a diversity of age, socio-economic and ethnic background in each recruitment area. To facilitate in-depth discussion and information provision[59], small groups of 7–9 participants attended each group (total $n = 49$). A further five were recruited but did not attend. Participants were recruited using a professional market research agency using a combination of face-to-face and online methods. Recruiters used a screening questionnaire and participants self-reported housing, professional and gender status. Participants received a £150 honorarium for taking part.

Data collection

To encourage reflection on the diverse disruptions that heat decarbonization and network upgrade may pose, we adopted a deliberative methodology involving a combination of information provision, group activities and discussions[59–62]. Each activity in the workshop protocol (Supplementary Information) was designed to highlight a specific way of relating to the home and the energy system. We thus aimed to offer participants a range of interpretive positions and resources to help make sense of heat decarbonization[23,63,64]. Sessions began with discussions about the local area and a doodle task where participants were asked to draw and discuss pictures depicting favourite spaces in their homes. These activities helped identify how participants relate to their homes in the present and to situate subsequent discussion of heating changes in the context of participants' homes and communities. To account for recent rises in the cost of living, 45 min was dedicated to discussing recent rises in energy bills and how participants were coping. Such discussions were helpful in gaining an insight into bill paying as a key relationship that citizens have with the energy system. At a time of heightened financial anxiety, this discussion was needed to acknowledge the financial strain that many people were experiencing and to ensure that subsequent talk of potentially costly heating technologies did not leave participants feeling frustrated and further marginalized.

Next, participants were shown a short presentation and fact sheets (Supplementary Information) summarizing the cost, environmental, in-home and network changes necessitated by heat networks, heat pumps, hydrogen boilers, hybrid systems and fossil fuel boilers. While the task concluded with participants ranking fact sheets in order of preference, the main aim was to encourage reflection on how and why specific changes may be disruptive, in the context of participants' homes and communities.

Subsequent discussions centred on how heat decarbonization may be organized in practice. This included a presentation detailing the successful state-led transition to natural gas in the 1960s and posters detailing potential business models and incentive packages proposed to assist uptake of low-carbon heating[65,66], 'do it yourself' (reflecting the status quo for citizens currently wishing to install a heat pump), one-stop shops, 'contracts for warmth' (product service systems) and local area energy planning (Supplementary Information). The aim was to examine how incentives and regulatory and network changes might disrupt expectations of home renovation and heating replacement. Workshops concluded with a personas' task[56] and reflections. Designed to elicit sympathetic reflection on how heat decarbonization may impact other people in their community, the personas used scenarios detailing specific in-home, regulatory and institutional changes that participants had to navigate using a character that they were tasked with creating (Supplementary Information). This drew together discussions from across the day and helped indicate that the forms of relationship that participants felt were particularly at risk of disruption.

Workshops were video and audio recorded and held between October 2022 and January 2023, in hotels or community centres close to the communities where participants were recruited. Workshops lasted approximately 7.5 hours each, including breaks. Lunch and light refreshments were provided at each venue.

Analysis

Data were transcribed by a professional transcription company and coded thematically in NVivo 12 by G.H.T.; participant names have been replaced with pseudonyms. Relationality is not a formal approach to risk analysis but rather reflects an approach to interpretation focused on the social and cultural relationships that render specific objects meaningful as risky, hazardous or, in this case, disruptive. Our analysis thus initially relied on thematic coding to identify the forms of object and relationship participants considered at risk of disruption from heat decarbonization. Coding followed an iterative process involving multiple readings and interpretation of the dataset and constant cross comparison between themes[67]. Initial readings of transcripts were used to develop index codes[68], signposting topics of discussion and ways of thinking about disruption that were used to ease navigation of the dataset. Initially, different forms of disruption (aesthetic and spatial impacts; construction; environment, health and safety; and financial implications) were coded separately for homes and networks.

As analysis proceeded, we identified an association between the perceived severity of a disruption and the extent to which it fell within expectations of ordinary relationships to infrastructure and home maintenance, renovation or homemaking. To preserve attention to specific relationships, index codes for disruption were not further aggregated into themes but rather compared against participants' individual descriptions of their homes and lives gathered in the early part of the workshop, and collective accounts of disruption within each separate group. Latter stages of analysis involved vertical comparison within the narrative statements of individual participants and group discussions, and cross-sectional comparisons between different participants and groups[69]. Working iteratively between individual narratives and across group comparisons allowed us to identify not only commonly perceived forms of disruption but also how and why these might matter in the lives of specific individuals and communities.

Limitations

While care was taken to ensure that presentations and fact sheet materials were accurate and balanced in terms of the information that they provided, during workshops, it became clear that discussions often centred on cost. Owing to uncertainty over future pricing, fact sheets used sliding scales to indicate relative differences in installation and operating costs for different technologies (Supplementary Information), whereas disruptions were listed in bullet point form in a separate box to facilitate examination of the relations impinged affected by specific material changes. At times, the eye-catching presentation of cost scales may have had an undue role in focusing attention of participants away from qualitative descriptions of disruption, an issue that moderators explicitly had to address by drawing participants' attention to disruption text boxes.

When combined with the study occurring at a time of uniquely high energy prices, it is possible that our findings overstate the importance that cost might have in other circumstances. However, information provided on emissions used a similar scalar representation and did not have the same role in shaping participant discussions. Moreover, while the study succeeded in adding depth and nuance to understandings of how inconvenience and disruption may be perceived, the importance of cost that we identified mirrors findings found in quantitative studies of heating perception conducted before recent price spikes[29].

Finally, this study shows the same trade-offs between depth and generalizability inherent to all interpretive research[68]. The qualitative nature of the analysis makes it impossible to separate out distinct variables such as social class and homeownership from other dynamics in each group. Thus, while our analysis suggests that dynamics of precarity and security shape perceptions of financial disruption, more focused quantitative analysis would be needed to assess the precise impact of income or ownership status. While the purposive sampling approach enabled us to examine in detail how specific patterns of housing and tenure shape perceptions of disruption, we cannot be sure how such perceptions would translate in different contexts. Further studies could investigate whether feelings of security and preferences for district heat in Liverpool would be replicated in other cities with similar patterns of housing but exhibiting different patterns of local and political identity. While several participants from the Scottish Borders lived in tenements, and several in other groups lived in houses of multiple occupancy, flats were not selected for close examination in this study as a high proportion are already served by resistive electric heating with network connections to match. However, given the challenges faced by households using this kind of heating[70], the limited space and high proportion of tenancy in this type of housing, further study should be a priority.

Ethics and inclusion

Ethical approval for the project was obtained from Cardiff University School of Psychology Research Ethics Committee (EC.22.07.12.6588GRA). Informed consent was obtained from all research participants.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data are not publicly available as they contain information that could compromise research participants' privacy and consents.

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Author contributions

The research was conceptualized by R.G., N.P. and K.H.; designed by G.H.T., J.F., J.S., K.H., N.P. and R.G.; data acquired by G.H.T., N.P., K.H. and F.S.; and data analysis and interpretation by G.H.T. and F.S. The paper was drafted by G.H.T. All authors contributed to revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Data analysis	Data was analysied usig Nvivo 12 software for qualitative data analysis.

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Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	We aimed to recruit roughly equal numbers of participants self-identifying as male or female and these are reported in the breakdown of participants in Table 1. Recruiters were instructed to include participants identifying as non-binary but none opted to participate.
Reporting on race, ethnicity, or other socially relevant groupings	Data was not collected on participant race or ethnicity and these were not categories used in analysis
Population characteristics	Recruitment was purposive in nature. A full explanation of the rationale and approach can be found in the methods section under 'Case selection and recruitment'.
Recruitment	Recruitment was conducted by a professional market research company and participants recieved a £150 honorarium for taking part.
Ethics oversight	Ethical approval for the project was sought and obtained from Cardiff University School of Psychology Research Ethics Committee (EC.22.07.12.6588GRA)

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Sample size	
Data exclusions	
Replication	
Randomization	
Blinding	

Behavioural & social sciences study design

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Study description	Qualitative- deliberative workshop methodology
Research sample	six workshop groups were recruited in Cardiff (x2); Gloucester; Liverpool (x2); and the Scottish Borders. 7-9 members of the public took part in each group, total n=49.
Sampling strategy	Sampling was stratified to ensure each group reflected a distinct set of relations to home and challenges posed by heat decarbonisation and network upgrade. Recruitment criteria were based on property age, location, and tenure. A full description can be fond in the methods section under case selection and recruitment
Data collection	Data was collected during six, one day deliberative worksops. Workshops were video and audio recorded, and transcripts furnished the data used for analysis.
Timing	Workshops took place between 8:45 and 16:15pm between October 2022 and January 2023
Data exclusions	No data has been excluded from the analysis
Non-participation	Of 54 participants recruited to the project, 5 failed to attend their workshop without giving notice or reason.
Randomization	n/a

Ecological, evolutionary & environmental sciences study design

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Study description	
Research sample	
Sampling strategy	
Data collection	
Timing and spatial scale	
Data exclusions	
Reproducibility	
Randomization	
Blinding	

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Field conditions	
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Antibodies

Antibodies used	
Validation	

Eukaryotic cell lines

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Laboratory animals	
Wild animals	
Reporting on sex	
Field-collected samples	
Ethics oversight	

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Clinical data

Policy information about clinical studies

All manuscripts should comply with the ICMJE guidelines for publication of clinical research and a completed CONSORT checklist must be included with all submissions.

Clinical trial registration	
Study protocol	
Data collection	
Outcomes	

Dual use research of concern

Policy information about dual use research of concern

Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

No	Yes	
☐	☐	Public health
☐	☐	National security
☐	☐	Crops and/or livestock
☐	☐	Ecosystems
☐	☐	Any other significant area

Experiments of concern

Does the work involve any of these experiments of concern:

No	Yes	
☐	☐	Demonstrate how to render a vaccine ineffective
☐	☐	Confer resistance to therapeutically useful antibiotics or antiviral agents
☐	☐	Enhance the virulence of a pathogen or render a nonpathogen virulent
☐	☐	Increase transmissibility of a pathogen
☐	☐	Alter the host range of a pathogen
☐	☐	Enable evasion of diagnostic/detection modalities
☐	☐	Enable the weaponization of a biological agent or toxin
☐	☐	Any other potentially harmful combination of experiments and agents

Plants

Seed stocks

Novel plant genotypes

Authentication

ChIP-seq

Data deposition

☐ Confirm that both raw and final processed data have been deposited in a public database such as GEO.

☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links
May remain private before publication.

Files in database submission

Genome browser session
(e.g. UCSC)

Methodology

Replicates

Sequencing depth

Antibodies

Peak calling parameters

Data quality

Software

Flow Cytometry

Plots

Confirm that:

☐ The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).

☐ The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).

☐ All plots are contour plots with outliers or pseudocolor plots.

☐ A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation

Instrument

Software

Cell population abundance

Gating strategy

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type

Design specifications

Behavioral performance measures

Imaging type(s)

Field strength

Sequence & imaging parameters

Area of acquisition

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software

Normalization

Normalization template

Noise and artifact removal

Volume censoring

Statistical modeling & inference

Model type and settings

Effect(s) tested

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference

(See Eklund et al. 2016)

Correction

Models & analysis

n/a	Involved in the study
☐	☐ Functional and/or effective connectivity
☐	☐ Graph analysis
☐	☐ Multivariate modeling or predictive analysis

Functional and/or effective connectivity

Graph analysis

Multivariate modeling and predictive analysis

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