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# Public perceptions of heat decarbonisation in Great Britain: Awareness, values and the social circle effect

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ABSTRACT

The decarbonisation of domestic heating is essential for the UK to achieve net zero carbon emissions, but requires significant changes in domestic infrastructure. Public participation plays a pivotal role in this transition, yet public attitudes towards decarbonised heating remain under-researched and poorly understood.

We report a nationally representative online survey of 2226 individuals in Great Britain. The survey explored attitudes to three decarbonised heating technologies currently being trialled or entering the market: heat pumps, hydrogen heating, and district heating networks. A wide dataset of interrelated variables was collected, including heating system preference and usage, knowledge and support for decarbonised heating, environmental and energy security concerns, perceptions of trust and responsibility, financial considerations, and many others.

Central to the study were two methodological innovations; an informed choice decision pathway element designed to investigate key factors underlying personal willingness to adopt each technology, and a psychometric network modelling approach that allowed deep exploration of the structural and dynamic properties of attitudes to decarbonised heating.

Findings indicated that the majority of respondents had were aware and supportive towards decarbonised heating, particularly towards heat pumps. However, knowledge of these technologies was limited. Government and energy actors were seen as somewhat untrustworthy but ultimately responsible for funding the transition, and respondents supported policies emphasising government responsibility.

When informed, respondent's willingness to adopt decarbonised heating technologies appeared resistant to change, and not strongly influenced any key factors. However, network modelling estimated normative social forces (‘social circle’ effect) were highly influential in shaping attitudes to decarbonised heating.

## 1. Introduction

The decarbonisation of heating technologies is a pivotal challenge for the transition to net-zero carbon emissions in the United Kingdom. Despite the presence of financial incentives and ambitious government targets (e.g. for increasing the sale and installation of heat pumps), achieving the changes to policy, energy markets, and public and domestic infrastructure necessary for national decarbonisation of heating is proving challenging in practice. This can be attributed to several coincident features of the UK energy landscape, including an aging housing stock with poor energy efficiency [1], slow planning procedures executed across outdated energy infrastructure, powerful fossil fuel incumbents allied to a system with existing high levels of customer satisfaction [2], and an economic situation that encourages fiscally conservative government policy. These to some extent represent archetypal challenges to heat decarbonisation that are encountered internationally. Difficult conditions for decarbonising heating are not unique to the UK. Germany, the Netherlands, France, Italy and parts of the USA still rely heavily on the use of natural gas for the heating of homes and businesses, and global progress towards decarbonising heating is currently stalling and at risk of falling behind IEA targets [3,4].

Whilst each of these features constitute complex barriers requiring intelligent answers from interdisciplinary science, at their core is the attitudes of the public – a central variable that has the potential to leverage the technological and policy-based solutions to addressing these challenges [5,6]. Technological solutions involve in a large part infrastructural changes in domestic spaces, as well as changes in

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behaviour and investments in emerging technologies at the level of individual members of the public. Similarly, changes to policy will rely on gaining a broad public mandate for change, and the success or failure of policy solutions designed to facilitate the transition to decarbonised heating is contingent on its compatibility with public expectations and priorities [7]. More generally, transitions in technology and energy use behaviour must to some extent be understood as social relational processes, shaped and enabled by interactions and affiliations between members of the public [8,9].

The UK in particular reflects the ongoing outcome of a heat decarbonisation pathway to date in which the importance of varied public groups[1] has been amplified further through government policy emphasising public agency. In the UK, government strategy has emphasised “maximizing consumer choice” between whichever low-carbon heating technologies become available [10], delegating the progress of the transition in part to market forces. Heat decarbonisation in the UK will therefore in part reflect the particular combination of technologies that conform to people's preferences. Whilst the direct influence of government policy is necessarily transient, the impact of policy at this nascent stage of the transition to decarbonised heating is likely to have long-lasting implications. Similarly, public attitudes are likely to be strongly influenced by the information context in which they were formed, which includes relevant policy communications that may unintentionally or intentionally emphasise certain beliefs [11]. Understanding how members of the public interact with heating technologies, how they are motivated to change these technologies where appropriate, and how the public values different aspects of heating technologies are therefore questions at the fulcrum of heat decarbonisation in the UK [12].

In the UK, there are broadly speaking three viable decarbonised heating technologies currently being trialled or entering the market; heat pumps, hydrogen heating, and district heating (otherwise known as heat networks). Heat pumps extract heat from the air or ground using an electric heat exchange system. Hydrogen heating entails burning hydrogen gas as an alternative to more conventional fossil gas, which releases little or no carbon when burned. Finally, district heating involves shared use of heat from a central source, circumventing any additional carbon emissions that would otherwise be produced by individual domestic heating systems. There is some debate regarding the extent to which each method is feasible at scale, and the extent to which each method can be decarbonised at supply-side. For example, considerable concern exists regarding the feasibility of synthesizing decarbonised ‘green’ or carbon-neutral ‘blue’ hydrogen, and whether existing gas infrastructure can be retrofitted at scale [13,14].[2] Likewise, the effective rollout of heat pumps in the UK likely relies on extensive upgrades to the national electricity supply grid, that are not yet addressed in government strategy [15].

### 1.1. Public perceptions and attitudes towards heat decarbonisation

A recent literature review capturing public attitudes to decarbonised heating [12] indicated that awareness for all low-carbon heating technologies in the UK is low, with high satisfaction for current gas heating systems. A variety of factors were found to potentially influence attitudes to decarbonised heating, from relatively pragmatic considerations relating to cost and performance, to more nuanced beliefs relating to perceptions of fairness and division of responsibility [16], and compatibility with personal and local narratives relating to heating and energy use [17]. Consistent with trends identified by government observatory data that have remained stable for several years [18], these findings show low awareness for all low-carbon heating technologies, paired with high satisfaction for current heating systems.

This review also highlighted influential factors particular to specific technology types. Considerations relating to everyday lifestyle were particularly salient for heat pumps, with necessary aspects of controlling and operating the technology challenging established expectations relating to heating use and comfort [19]. Concerns relating to the perceived cost of transitioning to hydrogen heating appeared influential [20]. More nuanced was the observation that the source of decarbonised heating appeared to be influential, with heat manufactured using a fossil fuel source being seen as less favourable [21]. This suggests the technological case for the manufacture of hydrogen (i.e. ‘blue’ or ‘brown’ hydrogen) is likely to be relevant to public preferences. Finally, trust in external actors was more salient as an influence for district heating, given the dependence on a shared external heating source, and the likely necessity of lock-in to a contract with an energy supplier.

In addition to these relatively grounded and pragmatic factors, previous literature has also identified relatively abstract factors. For example, climate concern appears to positively predict acceptance of an emerging energy technology [22], and broad environmental and personal values appear influential in shaping attitudes more broadly [23,24].

There are therefore a range of influential factors that may contribute to shaping attitudes towards decarbonised heating, which can be understood both within the context of the whole system transition (see [25]), and within the context of specific decarbonised heating technologies [12].

However, two major ambiguities remain in the understanding of public attitudes to decarbonised heating.

### 1.2. Key enabling factors driving acceptance of decarbonised heating

Firstly, it remains unclear whether amongst these factors there are a smaller number of key enabling factors that might strongly leverage attitude change, distinguishing those factors that are truly influential from those that are merely relevant. For example, it may be that whilst public attitudes towards a given technology are influenced by (e.g.) cost considerations, trust in energy suppliers, and level of thermal comfort, in practice it may be that one or another of these considerations leverage the orientation of the attitude above and beyond the other factors. In other words, whilst the contents of the landscape of public attitudes are well-documented, the shape of the landscape is relatively unknown.

Further complicating this, attitudes towards decarbonised heating might be assumed to be highly malleable due to the limited knowledge of the public regarding low-carbon heating technologies [26,27]. That is to say, although support for decarbonised heating is present [28] and has remained relatively stable [18,29], under conditions of low awareness attitudes exist in an unstable configuration that may be strongly perturbed by the introduction of salient new information. This may also further amplify the influence of these key enabling factors.

### 1.3. Dynamics and structures underlying public attitudes

Secondly, it is important to acknowledge that an ‘attitude’ is a multifaceted concept that has a number of possible theoretical interpretations. At one level, an ‘attitude’ may be taken to reflect an overall orientation towards an idea with a positive or negative valance. In our study, we examine this kind of positively or negatively valanced orientation towards decarbonised heating technologies as both general support (i.e. support for the use of these technologies in general) and personal willingness to use decarbonised heating given the opportunity,

[1] We use this term to describe members of the “general public”, without a specific background or stake in heat decarbonisation. However, it is important to acknowledge that the “public” is not a homogenous group. Multiple publics exist with different histories, agendas and cultural backgrounds, which meaningfully influence perceptions of technology and environment.

[2] Despite these concerns, UK government policy continues to maintain hydrogen as a viable decarbonised domestic heating option at the time of publication, and therefore we considered its inclusion in the survey necessary and appropriate.

capturing both to avoid an overly narrow conception of public approval [21,30]. However, we treat these measures as distinct to the more formal concept of an 'attitude' that we refer to in this study in the context of public attitudes.

There are several theoretical approaches to this formal conception of an attitude. Broadly, attitudes are frequently conceptualised as overarching objects that are described by a variety of evaluative reactions. Evaluative reactions are beliefs, emotions and behaviours that reflect and relate to the attitude object. This provides a relatively straightforward framework for understanding the underlying structure of an attitude. However, constructing a cohesive account of an attitude using this framework is not straightforward. Publics are not abstracted homogenous groups, but rather a diverse and dynamic congress of interacting populations, where granular differences within publics are highly influential. Furthermore, an obvious but non-trivial feature of publics is that they consist of human actors, who do not express attitudes using simple input-output computation, but rather are subject to biases, estimations and heuristics. As a result, public attitudes must be understood as interrelated structures consisting of a large number of variables.

Here we employ Causal Attitude Network theory (CAN; [31]) to provide a framework for this approach, describing attitudes as objects consisting of causally linked evaluative reactions that exert influence over one another, and collectively predict the state of the attitude as a whole. Importantly, CAN suggests that evaluative reactions are also influenced recursively by the attitude object itself, as it exerts top-down influence to reduce inconsistencies. This makes the model well suited to studying public attitudes, which can simultaneously be understood both as more than a sum of their parts (i.e. as an 'attitude object' in itself) and as a collection of underlying variables (i.e. the multitude of factors that reflect and influence the attitude object). We therefore use CAN as the framework for understanding and discussing public attitudes in this study.

### 1.4. Methodological approach and aims

In the present study, we explore these two ambiguities through a nationally representative survey that collected a wide range of factors relevant to public attitudes to decarbonised heating. Specifically, to address the first ambiguity we aimed to explore key enabling factors driving willingness (or not) to adopt decarbonised heating technologies, from within a defined set of factors known to influence acceptance of heating technologies and emerging technologies more generally. For example, Becker et al. (2023) highlighted several directly influential sociotechnological factors, and values relating to sustainability also appear influential [22–24]. Simultaneously, we aimed also to replicate the effect of these previously reported factors in the context of a single survey and sample, providing a unified description of public attitudes to decarbonised heating that had otherwise been described disparately by numerous independent studies. In addition to the utility provided by this self-contained account, replication remains vitally important for enhancing the integrity of this area of social psychological research, concerned as it is with measuring attitudes where effect sizes are typically weak [32,33].

To investigate the second ambiguity described above, we aimed to provide a comprehensive and deep causal network model of the structure and dynamics underlying public attitudes to decarbonised heating as a unified attitude 'object'. In other words, in addition to exploring dynamics within a set of known factors, we also explore novel patterns of interaction between factors that emerge from investigating a broader and more cohesive model of an attitude. Furthermore, in addition to allowing the more complex structure of public attitudes to decarbonised heating to be explored, this latter aim will also provide a more general descriptive account of public attitudes towards decarbonised heating in the UK that may complement existing government tracker data and provide an indication of broad trends amongst the public.

To achieve these aims, we used two methodological innovations; an informed choice and decision pathway element, and a psychometric network modelling approach.

The former involves providing respondents with a basic level of information regarding the decarbonised heating technology in question, sufficient to allow them to make a hypothetical judgement of whether (or not) they would be willing to adopt a technology. This judgement was then scrutinised using a decision pathway element. Decision pathway elements provide opportunities to create 'junctions' in the flow of a survey where between-groups differences in respondents can be elicited, isolated, and explored [34,35]. In our survey, this element divided respondents based on their initial position of (un)willingness, and then invited respondents to consider how their position might change given a variety of positive and negative hypothetical scenarios (each representing a specific factor, e.g. cost, environmental friendliness) that might be associated with adoption of each specific technology. This element is central to investigating the presence of key enabling factors, as it allows an explicit assessment of the degree to which a given factor (as represented in each hypothetical scenario) is influential in shaping willingness to adopt each technology. More generally, but no less importantly, through using this method respondent attitudes can be assessed and explored in the same standardised information context, which is of particular importance given that is expected (as described above) that many participants may know very little about decarbonised heating.

The latter methodological innovation allows us to embrace the potential scale and complexity of the factor structure of an attitude, whilst responding to the challenges of achieving this in practice. Specifically, the methodological challenge presented by understanding an attitude through the CAN framework is that capturing a large number of variables does not arbitrarily increase precision, but rather increases the complexity of the attitude object being described. This renders the comprehensive network description of an attitude provided by CAN theoretically compelling but practically difficult. However, we address this methodological challenge using psychometric network modelling [36,37], a technique that allows many interrelated variables to be understood as a sparse undirected network that collectively represents the attitude object being studied. Beyond being solely a method of data visualisation, this technique provides a rigorous quantitative description of the attitude, both at a granular (i.e. individual relationships between variables) and whole-network level (i.e. emergent structures across variables). Importantly, its sparseness helps circumvent spurious relationships that might otherwise be encountered when analysing a large attitudes dataset, whilst its undirected approach helps to reflect the nuance and interrelated nature of attitudes by avoiding a potentially reductive causal description of the relationship between variables.

This method (described in detail below) represents an emerging technique in social psychology [38], that is to some extent reflective of contemporary approaches to the psychology of attitudes more generally (Dalege et al., 2016). Several experimental environmental psychology studies have already utilized psychometric network modelling to investigate attitudes [39–41]. In the present study, we demonstrate its successful application to a larger dataset than has previously been attempted.

Taken together, we provide a cohesive account of public attitudes to decarbonised heating, containing both a description of general trends characterising public perceptions and preferences, a focused investigation of key factors (if any) that strongly leverage public willingness to adopt decarbonised heating technologies, and a deep network description that is able to explore the complex (and possibly novel) structural and dynamic properties that underlie public attitudes.

## 2. Methods

### 2.1. Sample

2266 respondents were recruited from a panel provided by Qualtrics, a major third-party survey recruitment company (see Supplementary Table A for sample demographics). Respondents were recruited via quota sampling between February and March of 2023, using nationally representative quotas for region, gender, age, and level of education. Respondents were provided with an inconvenience allowance by the recruitment company as compensation for their participation. Only respondents that fully completed the survey were included in the sample.

### 2.2. Survey instrument

The survey was designed based on key factors identified previously as being related to perceptions of emerging technologies and decarbonised heating more specifically (as described above; see [12]). The survey was administered online, and consisted of 100 items separated into distinct sections capturing: individual and situational demographic traits, perceptions of climate change, heating knowledge and awareness, current heating system use and relevant behavioural dynamics, knowledge of LCH technologies, informed support and willingness to adopt LCH technologies (i.e. informed choice element), environmental values, and perceptions of trust, responsibility and fairness concerning the transition to decarbonised heat. Additionally, due to their particular salience given the contemporary context of the survey, items relating to financial context were also included. Finally, to capture the extent to which decarbonised heating featured in a respondent's social environment, a single item was added assessing this (i.e. "Do you know of anyone ['no-none / one / several'] who currently uses a low-carbon heating system?"). These items were encoded using a variety of scales, some of which followed a general format (e.g. 5-point Likert-style scales) and some of which were tailored specifically to the item (e.g. selecting from a number of applicable statements). Only a subset of these 100 items are featured in the analysis that is the content of this study, with the rest explored in future publications (see Supplementary Information D for a complete description of all items featured in this study). Responses to these items were structured as Likert-style scales and required little to no processing (details of any processing or additional encoding are provided in section 2.3).

#### 2.2.1. Informed choice element

As part of the informed choice element, respondents viewed three information cards containing information relating to heat pumps, hydrogen heating, and district heating respectively (see Supplementary Information C). The order in which the cards were viewed was randomized.

Each information card featured a picture of the technology in-situ (or the closest approximation, e.g. a photo of district heating supply pipes) and a short description of the technology and how it provides heat. Each card then featured a deeper description of the technology in terms of six categories; running cost, installation cost, control (i.e. "how to use"), environmental friendliness, technological readiness, and level of disruption necessary for the installation. The information provided was sourced from academic or third sector analysis where possible as opposed to information from invested parties (i.e. manufacturers).

In each category, the information was presented in a neutral tone, avoiding unnecessary speculation, evaluation or comparison with alternative technologies. However, in order to make information regarding running costs more easily intelligible, the cost of existing natural gas heating was used as a reference.

For some technologies, where only speculative information was available regarding one or more aspects of the technology, it was necessary to provide a more general description. For example, given the limited deployment of hydrogen heating compared to heat pumps, the information provided regarding the former was necessarily less detailed than the latter.

#### 2.2.2. Decision pathway element

Following the informed choice element, respondents completed a simple decision pathway element, where they were asked to make a statement about their personal willingness to adopt each decarbonised heating technology, that was then further evaluated in a short sequence of following questions. Importantly, respondents were specifically asked whether they would adopt each technology given a hypothetical opportunity to do so (e.g. invitation to a local hydrogen heating trial). This question was also worded to provide an altered context tailored to respondents in rented accommodation, specifically "If you are renting, imagine your landlord is considering these options and asking for your opinion". It is noteworthy that this item did not provide respondents with the option of an ambivalent answer, but rather required respondents to express if they would be willing or unwilling to act if given an opportunity (i.e. where ambivalence would not be meaningful, or arguably tantamount to an unwilling position). However, respondents were given the opportunity to qualify their position as 'somewhat' willing or unwilling, allowing some indication of a tentative attitude.

Once respondents had expressed their willingness or not to adopt a technology given a specified hypothetical scenario, they were shown a series of eight further hypothetical scenarios relating to the adoption of the technology. These scenarios presented various positive or negative potential consequences of adopting the technology. For example, for heat pumps, respondents were presented with a scenario in which no government subsidies were provided (negative) and presented with a scenario in which a 24/7 support line was available post-installation (positive). In each case, respondents were asked to consider whether this scenario would make them more or less willing, relative to their initial position of being willing or unwilling to adopt the relevant decarbonised heating technology. This was operationalised as an evaluation rating of each scenario with either a positive, neutral or negative valence (e.g. whether each scenario was evaluated negatively as decreasing willingness to adopt technology, positively as increasing willingness. or neutrally as having no impact on willingness).

### 2.3. Data analysis

#### 2.3.1. Exploratory analyses of within-groups differences in attitudes

In order to investigate broad within-groups differences in key attitudes towards decarbonised heating technologies and the transition to decarbonised heating in general, a series of one-way repeated measures ANOVA analyses were conducted.

To investigate key differences in attitudes towards different technologies, three analyses were performed where the independent variable was technology type (heat pumps, hydrogen heating, or district heating), and the dependent variable was either degree of support (for adoption of the technology across the UK), personal willingness to adopt (given a specified hypothetical scenario), or extent of knowledge regarding the technology respectively.

The perceived relative importance of decarbonising heating versus other emission-reducing actions and other decarbonising sectors were examined in two analyses, where the independent variable was action or sector type, and the dependent variable was the level of perceived importance.

Differences in perceptions of trust and responsibility towards actors involved in the transition to decarbonised heating were explored in three analyses, where the independent variable was actor type, and the dependent variable was either trust in terms of information provision, trust in decision making, and perceived responsibility (for financing the transition specifically).

Finally, attitudes towards different policy options for facilitating the transition to decarbonised heating were explored in a single analysis, where the independent variable was policy type, and the dependent variable was degree of support for the policy in question.

#### 2.3.2. Decision pathway element analyses

We investigated whether initial willingness to adopt decarbonised heating influenced how respondents reacted to the eight positive and negative scenarios included in the decision pathway element. In order to do this, a series of two-way (2 × 2) mixed measures ANOVA analyses were performed, where independent variables were initial willingness to adopt decarbonised heating (willing / unwilling, for each technology type) and the valence of each hypothetical scenario type (positive / negative). In each analysis, the dependent variable was mean evaluation rating across all scenarios. For these analyses, the item assessing initial willingness to adopt decarbonised heating was transformed from a 4-point scale into a binary scale, where 'very willing/somewhat willing' responses and 'very unwilling/somewhat unwilling' responses were compounded together into 'willing' and 'unwilling' respectively. Bonferroni correction was applied to all analyses to control for multiple comparisons.

To further explore responses to the decision pathway element, we used regression analyses to explored the factor structure underlying between-groups differences in initial willingness to adopt decarbonised heating. Three binary logistic regression analyses were performed to assess the predictive influence of each variable in the decision pathway decision pathway section on willingness to adopt decarbonised heating. In each analysis, the independent predictor variables were evaluation ratings for each of the eight positive and negative hypothetical scenarios. The outcome variable in each analysis was willingness (willing or unwilling) to adopt hydrogen heating, heat pumps, or district heating respectively.

#### 2.3.3. Psychometric network modelling

To perform a deep investigation of the overall factor structure of attitudes to decarbonised heating in our dataset, a weighted undirected[3] network model was generated using the *graphical LASSO* (glasso) method, using the *qgraph* package for *R Studio* [42]. This method transforms a dataset of continuous variables into a polychoric correlation matrix that is then used to estimate a partial correlation network. Each variable is regressed onto all other variables, generating a matrix of estimated parameters (partial correlation coefficients) representing the strength of connection between each variable and all other variables in the dataset. This can then be visualized as a weighted network, where each variable is represented as a node, with the connections ('edges') between each node weighted based on the estimated parameters.

Importantly, the *glasso* method is not solely a means for network estimation, but also features rigorous statistical regularisation as well as model selection via the LASSO (least absolute shrinkage and selection operator) and EBIC (extended Bayesian information criterion) techniques respectively. The former allows for the creation of a sparse network with many weaker or more spurious edges pruned from the model, whereas the latter allows for the selection of the best fitting model from a set of potential models with varying degrees of regularisation.

The result is a cohesive overview of the structure of the dataset, regularised to produce the best fitting set of relationships between variables.

In order to investigate of the detailed structure of this network (see [36] for a comprehensive description of the approach taken), node centrality indices were calculated, measuring strength (the sum of all absolute edge weights between each node and its neighbours), closeness (the inverse of the shortest path length between each node and all other nodes), and betweenness (the number of shortest paths each node lies on). Bootstrapped difference tests for centrality indices between-nodes were calculated using the Bootnet package [43]. Bootstrapping was also used to calculate edge weight precision and central stability, which measure the reliability of the estimated network model. Predictability was also calculated for each node, representing how much variance in each node was explained by its weighted connections with adjacent nodes, providing a metric both of predictability between nodes, and across the network as a whole. Finally, nodes were clustered into communities (interconnected subnetworks) using the Walktrap algorithm.

## 3. Results

### 3.1. Exploratory analyses of within-groups differences in attitudes

#### 3.1.1. Support, awareness and willingness to adopt decarbonised heating

Respondent levels of support, awareness and willingness to adopt each technology type were characterised superficially by a similar pattern, with respondents expressing generally high levels of affirmation for each, but with a similarly high proportion of respondents undecided or unsure (see Fig. 1 for an example of this pattern in the context of support for each technology).

A one-way within-subjects ANOVA indicated a significant main effect of technology type on degree of support ($F(2,2256) = 57.05$, $p < .001$), willingness to adopt the technology given a hypothetical opportunity ($F(2,2264) = 9.26$, $p < .001$), and level of awareness and knowledge ($F(1,2264) = 258.52$, $p < .001$). Post-hoc testing indicated that degree of support, and level of knowledge and awareness was significantly greater for heat pumps compared to hydrogen, and district heating ($p < .001$ for all results). Willingness to adopt the technology was significantly greater for both heat pumps ($p < .001$) and hydrogen ($p < .001$) compared to district heating, but no significant difference was observed between heat pumps and hydrogen ($p = .518$).

#### 3.1.2. Perceived importance of decarbonising heating for addressing climate change

A one-way within-subjects ANOVA indicated a significant main effect of emission-reducing behaviour type on perceived importance ($F(4,2258) = 165.97$, $p < .001$). Post-hoc testing indicated that ratings of perceived importance for using decarbonised heating at home were significantly lower than reducing domestic energy use more generally ($p < .001$), but were significantly greater than other behaviours such as eating less red meat ($p < .001$), reducing consumption of goods ($p = .011$), and limiting air travel ($p = .006$).

Similarly, we observed a significant main effect of sector type on perceived importance ($F(6,2259) = 175.59$, $p < .001$). Post-hoc testing indicated that ratings of perceived importance for the heating and cooling of buildings were significantly lower compared to the transport, primary materials and consumer materials sectors of carbon emissions (for all results $p < .001$), but significantly higher than the waste ($p = .012$), electricity ($p < .001$) and agriculture ($p < .001$) industries.

#### 3.1.3. Perceived trust in actors involved in the transition to heat decarbonisation

Two one-way within-subjects ANOVAs indicated a significant main effect of actor type on perceived trust to provide information ($F(2,2243) = 444.21$, $p < .001$) and make decisions ($F(2,1063) = 575.32$, $p < .001$) regarding the transition to decarbonised heating. Post-hoc testing indicated that for both analyses, respondents trusted themselves higher than both government and energy sector actors, and that government actors were perceived less trustworthy than energy sector actors (for all results $p < .001$).

#### 3.1.4. Perceived responsibility for financing the transition to heat decarbonisation

A significant main effect was also observed of actor type on perceived responsibility to finance the transition ($F(3,2252) = 114.64$, $p < .001$). Post-hoc testing indicated that consumers were perceived as bearing significantly less responsibility to pay than government ($p < .001$), energy sector actors ($p < .001$) and home-owners more specifically ($p < .001$). Home-owners were perceived as bearing significantly less responsibility than government ($p < .001$) and energy sector actors ($p < .001$). Government and energy sector actors were perceived as bearing

[3] A network is 'weighted' if it is organised based on estimated parameters, and 'undirected' if connections ('edges') between nodes are bidirectional.

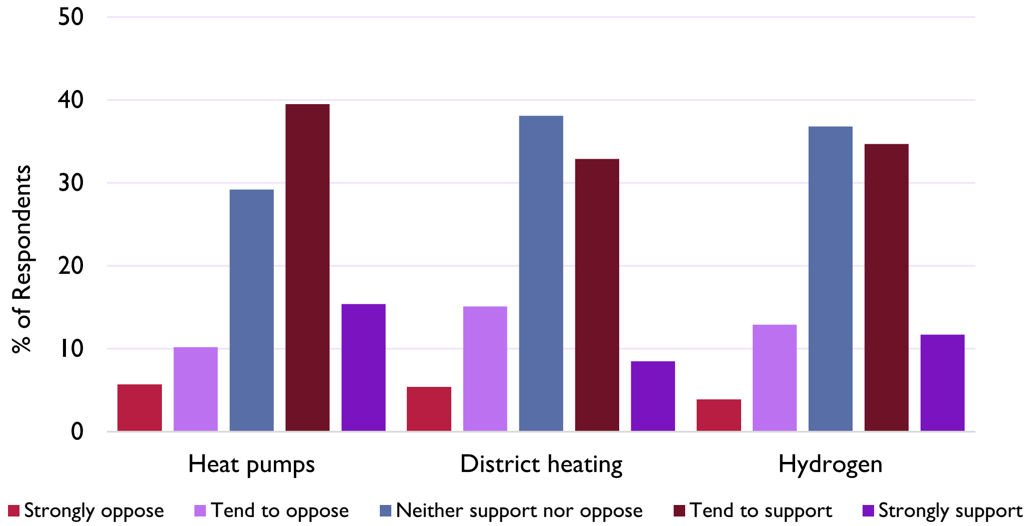


**Fig. 1.** Graph showing the proportion of respondents supportive, undecided or opposed to the introduced of decarbonised heating technology across the UK, after receiving information about the technologies.

equivalent responsibility ($p = .71$).

*3.1.5. Support for policies facilitating the adoption of decarbonised heating*

Finally, a one-way within-subjects ANOVA indicated a significant main effect of policy type on degree of support ($F(2,2255) = 594.97$, $p < .001$). Post-hoc testing indicated that support for the provision of subsidies for the installation of a heat pump was significantly greater than support for the inclusion of decarbonised heating systems in all new-build properties ($p = .016$) and the ban on the sale of new oil and gas boilers ($p < .001$). Support for the ban on the sale of new oil and gas boilers was significantly lower than including decarbonised heating in new-build properties ($p < .001$).

*3.2. Decision pathway results: willingness to adopt heating technologies under different hypothetical scenarios*

*3.2.1. Hydrogen heating*

For hydrogen heating, 1469 respondents (64.7 %) reported they would be willing to adopt the technology if a trial was hypothetically launched in their area, whereas 780 respondents (34.4 %) reported they would be unwilling. 17 respondents (0.75 %) did not answer.

A two-way (2 × 2) mixed measures ANOVA indicated a significant interaction between an individual's initial position of willingness or unwillingness to adopt hydrogen heating, and positive or negative scenario type, on evaluation ratings of the hypothetical scenarios ($F(1,2247) = 5.22$, $p = .02$). This suggests the extent to which an individual's evaluations are influenced by the valence of the hypothetical scenario depends on their initial willingness to adopt the technology. Estimated marginal means indicated that individuals who were initially willing to adopt hydrogen heating evaluated both negatively and positively valanced hypothetical scenarios more positively than those who were initially unwilling, but that individuals who were initially willing had a greater degree of difference between their evaluations of positively and negatively valanced scenarios.

A binary logistic regression model was statistically significant [$\chi2(8) = 29.88$; $p < .001$], indicating the extent to which hypothetical scenarios were rated as influential successfully predicted an individual's initial position of willingness or unwillingness. Model estimates suggested that more positive evaluations of all hypothetical scenarios (i.e. that the scenario would make the respondent more positive towards the given technology) significantly increased the odds of being initially willing to adopt hydrogen heating (see Table 1 for all results). In particular, the scenario relating to reduced running costs had the highest predictive value, with every unit increase in evaluation of the scenario associated with a 2.03 times higher likelihood of being initially willing to adopt hydrogen heating (95 % CI 1.73–2.37).

**Table 1**
Binary logistic regression results for the hydrogen decision pathway element analysis. The exact wording of each hypothetical scenario presented to respondents is shown (scenarios 1–4 are positive, 5–8 are negative).

| | B | S.E. | Sig. | Exp (B) | 95 % C.I.for Exp (B) | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Running costs are cheaper than your current heating system. | 0.709 | 0.080 | 0.000 | 2.032 | 1.737 | 2.376 |
| Other neighbourhoods have already completed trials successfully. | 0.404 | 0.078 | 0.000 | 1.497 | 1.284 | 1.746 |
| A 24 h support team is available to help with any issues. | 0.297 | 0.077 | 0.000 | 1.345 | 1.156 | 1.565 |
| Your home could be made compatible with hydrogen with only minimal disruption. | 0.456 | 0.072 | 0.000 | 1.578 | 1.369 | 1.818 |
| You are not able to switch back to your old heating system after the trial finishes. | 0.155 | 0.067 | 0.021 | 1.168 | 1.024 | 1.333 |
| Running costs are NOT cheaper than your current system. | 0.217 | 0.075 | 0.004 | 1.243 | 1.073 | 1.440 |
| A previous trial found some safety issues. | 0.343 | 0.076 | 0.000 | 1.409 | 1.214 | 1.636 |
| All heating appliances in your home have to be switched to hydrogen ready appliances. | 0.170 | 0.063 | 0.007 | 1.185 | 1.046 | 1.341 |

*3.2.2. Heat pumps*

For heat pumps, 1411 respondents (62.2 %) reported they would be willing to adopt the technology when next replacing their existing heating system, whereas 843 respondents (37.20 %) reported they would be unwilling. 12 respondents (0.52 %) did not answer.

A two-way (2 × 2) mixed measures ANOVA indicated a main effect of an individual's initial position of willingness or unwillingness to adopt a heat pump ($F(1,2252) = 813.93$, $p < .001$), and a main effect of positive or negative scenario type ($F(1,2252) = 2275.43$, $p < .001$), on evaluation ratings of the hypothetical scenarios, but no significant interaction effect ($F(1,2252) = 0.086$, $p = .69$). Estimated marginal means indicated evaluations of positively valanced scenarios were more positive than those of negatively valanced scenarios, and that individuals who were initially willing to adopt a heat pump evaluated all hypothetical scenarios more positively than those who were initially unwilling.

A binary logistic regression model was statistically significant [$\chi2$ (8) = 35; $p < .001$], indicating the extent to which hypothetical scenarios were rated as influential successfully predicted an individual's initial position of willingness or unwillingness. Model estimates suggested that more positive evaluations of all hypothetical scenarios significantly increased the odds of being initially willing to adopt a heat pump (see Table 2 for all results). In particular, the scenario relating to reduced running costs had the highest predictive value, with every unit increase in evaluation of the scenario associated with a 1.83 times higher likelihood of being initially willing to adopt a heat pump (95 % CI 1.58–2.12).

#### 3.2.3. District heating

For district heating, 1265 respondents (55.8 %) reported they would be willing to adopt the technology if a heat network was established in their area, whereas 811 respondents (35.7 %) reported they would be unwilling. 190 respondents (8.38 %) did not answer.

A two-way (2 × 2) mixed measures ANOVA indicated a main effect of an individual's initial position of willingness or unwillingness to adopt district heating ($F(1,2074) = 699.15$, $p < .001$), and a main effect of positive or negative scenario type ($F(1,2074) = 1382.79$, $p < .001$), on evaluation ratings of the hypothetical scenarios, but no significant interaction effect ($F(1,2074) = 0.88$, $p = .13$). Estimated marginal means indicated evaluations of positively valanced scenarios were more positive than those of negatively valanced scenarios, and that individuals who were initially willing to adopt district heating evaluated all hypothetical scenarios more positively than those who were initially unwilling.

**Table 2**
Binary logistic regression results for the heat pump decision pathway element analysis. The exact wording of each hypothetical scenario presented to respondents is shown (scenarios 1–4 are positive, 5–8 are negative).

| | B | S.E. | Sig. | Exp (B) | 95 % C.I.for Exp (B) | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| The government would help with some of the installation costs. | 0.392 | 0.074 | 0.000 | 1.480 | 1.279 | 1.712 |
| Many people in your neighbourhood already have a heat pump. | 0.215 | 0.078 | 0.006 | 1.240 | 1.065 | 1.445 |
| The heat pump is cheaper to run than your current system. | 0.606 | 0.076 | 0.000 | 1.833 | 1.580 | 2.126 |
| Full warranty and a 24 h support team is provided to help with any issues. | 0.369 | 0.078 | 0.000 | 1.447 | 1.241 | 1.687 |
| There are no grants available to help with installation costs. | 0.278 | 0.062 | 0.000 | 1.320 | 1.169 | 1.490 |
| The heat pump will take 5 days to install. | 0.190 | 0.065 | 0.003 | 1.210 | 1.065 | 1.374 |
| You find out your home needs additional insulation and/or a water tank installed to make the heat pump efficient. | 0.241 | 0.068 | 0.000 | 1.273 | 1.114 | 1.454 |
| It is necessary to change radiators to underfloor heating or change radiators to larger ones. | 0.198 | 0.063 | 0.002 | 1.218 | 1.076 | 1.380 |

A binary logistic regression model was statistically significant [$\chi2$ (8) = 25.25; $p < .001$], indicating the extent to which hypothetical scenarios were rated as influential successfully predicted an individual's initial position of willingness or unwillingness. Model estimates suggested that more positive evaluations of all hypothetical scenarios significantly increased the odds of being initially willing to adopt district heating (see Table 3 for all results). In particular, the scenario relating to the supplier having a positive reputation had the highest predictive value, with every unit increase in evaluation of the scenario associated with a 1.8 times higher likelihood of being initially willing to adopt hydrogen heating (95 % CI 1.53–2.11).

### 3.3. Psychometric network modelling

#### 3.3.1. Network estimation

The network model estimated is displayed in Fig. 2. The strength and influence (positive or negative) of edges is represented as thickness and colour (green or red) respectively. Communities are categorized by colour and represented as clusters of nodes. Node placement is dictated based on the Fruchterman-Reingold algorithm [44], wherein nodes that are stronger and more connected are given a more central position relative to the rest of the network. Likewise, nodes are positioned within- and between communities based on their strength and connectedness relative to other nodes.

Several superficial features of the network are evident. Seven

**Table 3**
Binary logistic regression results for the district heating decision pathway element analysis. The exact wording of each hypothetical scenario presented to respondents is shown (scenarios 1–4 are positive, 5–8 are negative).

| | B | S.E. | Sig. | Exp (B) | 95 % C.I.for Exp (B) | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| New heat networks have been successfully set up in many other neighbourhoods. | 0.561 | 0.081 | 0.000 | 1.753 | 1.497 | 2.054 |
| The supplier providing your heat network has an excellent reputation amongst their customers. | 0.589 | 0.082 | 0.000 | 1.802 | 1.536 | 2.115 |
| Joining the heat network would noticeably increase the sense of community between you and your neighbours. | 0.354 | 0.083 | 0.000 | 1.425 | 1.212 | 1.676 |
| The heat supplied to the network is waste heat provided by an environmentally friendly industry. | 0.186 | 0.069 | 0.007 | 1.204 | 1.052 | 1.378 |
| The heat supplied to the network is waste heat from an environmentally damaging industry. | −0.090 | 0.053 | 0.091 | 0.914 | 0.824 | 1.015 |
| You have to sign up to a 24 months contract with the heat supplier. | 0.236 | 0.067 | 0.000 | 1.266 | 1.109 | 1.445 |
| Setting up the heat network would cause a few days of disruption to you and your neighbours. | 0.203 | 0.073 | 0.005 | 1.225 | 1.061 | 1.413 |
| A maintenance issue in a neighbouring property could cause disruption to your heating. | 0.405 | 0.069 | 0.000 | 1.500 | 1.309 | 1.718 |

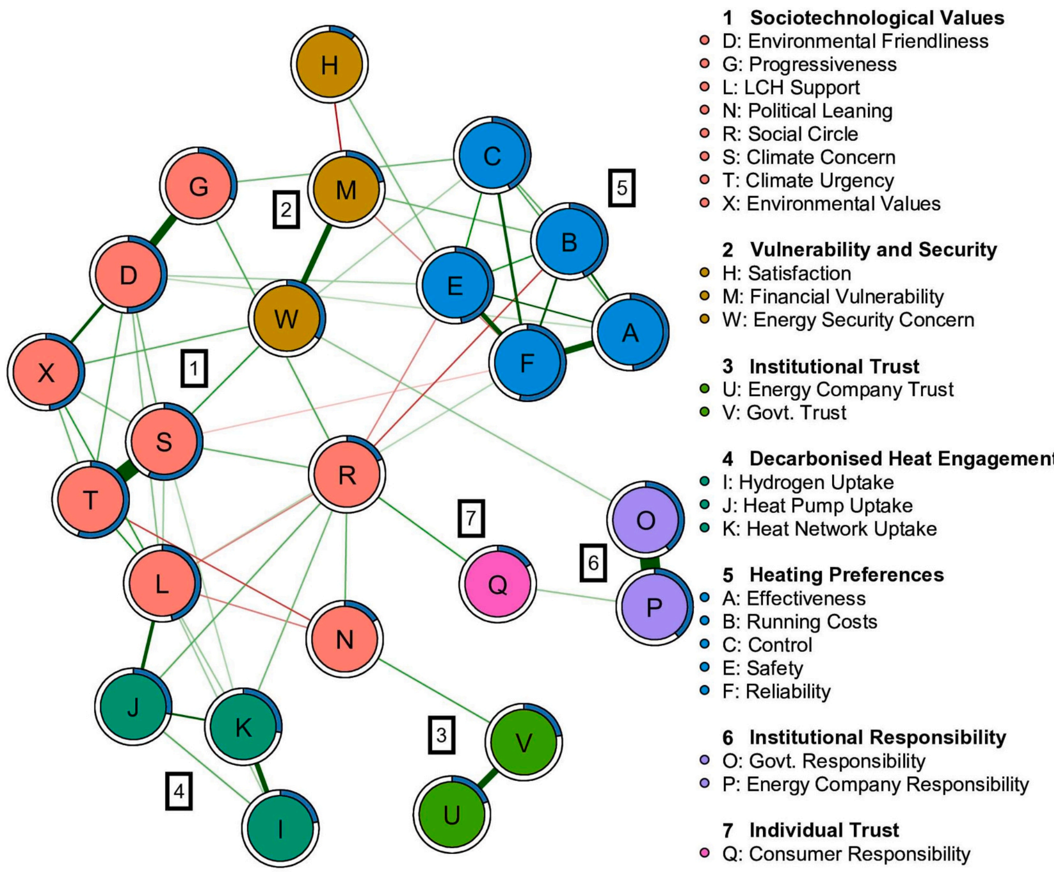


**Fig. 2.** Estimated undirected network. Connections (edges) between nodes highlight conditional relationships between specific variables, whereas the overall arrangement and connectivity of all nodes in the network highlight structural and dynamic features of attitudes towards decarbonised heating as a whole. Edge colour indicates the direction of the relationship between nodes (green – positive, red – negative). Edge thickness denotes the strength of the relationship between nodes. The ring segments surrounding nodes indicate the variance explained by all connections with neighbouring nodes. Node colours indicate community clusters, described by the key provided. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

communities were detected. Communities such as 'heating preferences' or 'LCH engagement' represent clusters of highly related variables. Other communities represent more diverse clusters, such as 'sociotechnological values', which includes social and pro-environmental beliefs, or 'vulnerability and security', which includes concerns regarding national and domestic stability. Finally, 'institutional trust' and 'institutional responsibility' respectively are clustered as distinct nodes.

The number and distribution of connections appears relatively sparse, with connections within communities being relatively strong, but communities themselves being otherwise somewhat isolated from one another. The exception appears to be the 'Sociotechnological Values' community, which is situated in a central position and has a greater degree of connectivity with other communities across the network. Within this community, 'social circle' emerges as the node with the most central position and the greatest number of edges connecting to different communities. This variable refers to the survey item capturing the extent to which decarbonised heating systems featured in a respondent's social environment (i.e. "Do you know of anyone ['no-none / one / several'] who currently uses a low-carbon heating system?").

The precision of edge weights was estimated via the bootstrapping procedure described by Hevey [36]. A plot of bootstrapped weights (bootN = 1000; see Supplementary Fig. B2) indicated edges were highly stable. Similarly, bootstrapped difference tests were conducted to test for statistically significant differences in edge weights. Results indicated stronger edges were on the whole significantly greater than weaker edges (see Supplementary Fig. B3).

Node predictability is displayed as a ring around each node, with the coloured portion of each ring indicating the amount of variance explained by connections with neighbouring nodes.

### *3.3.2. Node centrality*

Node centrality metrics are displayed in Fig. 3. Fig. 2 suggests high strength values largely reflect nodes within communities featuring multiple strongly connected neighbours, and do not therefore necessarily suggest a noteworthy influence across the network. When examining betweenness and closeness values, 'social circle' stands out as markedly higher than all other variables, indicating the node is highly central and acts as a bridge between communities, and is therefore likely to exert influence across many other nodes in the network.

The stability of centrality metrics was estimated via case-dropping bootstrapping (bootN = 1000; see Supplementary Fig. B1), wherein the correlation between the sampled and bootstrapped centrality metrics is calculated as the bootstrapped sample drops to 25 % of the original sample size. When the correlation falls below 0.7, the centrality metrics are no longer considered stable. The proportion of the original sample at which this threshold is crossed therefore acts as a measure of confidence in the centrality metrics for the original sample (the 'correlation stability coefficient'), with a low threshold indicating low reliability. Our estimated network all centrality metrics were highly stable, with a correlation stability coefficient $\geq 0.50$ for each.

Finally, bootstrapped difference tests were conducted to test for significant differences in centrality metrics. Results indicated that 'social circle' had significantly greater betweenness and closeness than other many nodes in the network (see Supplementary Figs. B4 – B5).

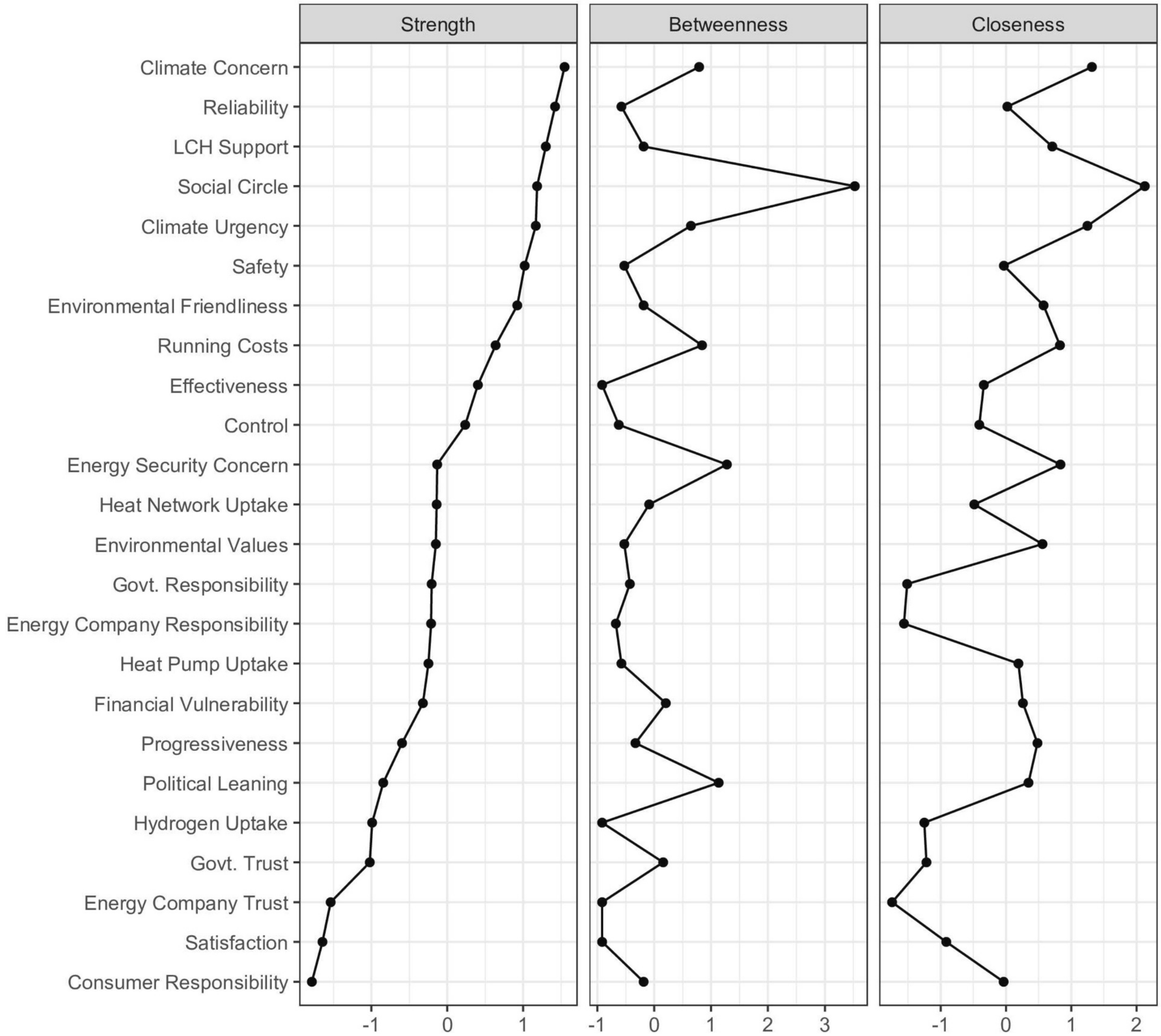


**Fig. 3.** Plot showing centrality estimates for each node in the network. Strength (absolute sum of connection strengths with neighbouring nodes), betweenness (the number of shortest paths between nodes a given node is located on, and closeness (the average shortest path length between a given node and all other nodes in the network).

## 4. Discussion

In accordance with our expectations, we found a variety of trends and salient factors that corroborate and elaborate on those identified by previous research (see [12]). Our two exploratory methodological innovations, a decision-pathway element and psychometric network modelling respectively, highlighted several findings novel to this area of research. In particular, the central importance of normative 'social circle' forces indicated by the latter.

### *4.1. Public support for decarbonised heating*

Our results indicate significant support amongst the sample for decarbonised heating technologies, with a higher proportion supporting rather than opposing each technology after being provided with relevant information. Similarly, a higher proportion of respondents were also willing to adopt each technology following information provision. This is indicative of a level of enduring support and optimism for decarbonised heating evident elsewhere in the literature [18,45], and one that appears robust to uncertainties and a contemporary context of relatively widespread financial hardship [29].

However, this is interpretation is partially contingent on framing our findings simply in terms of support versus opposition. A large number of our respondents held an ambivalent or neutral position versus those who supported each technology. Hence, whilst public attitudes towards decarbonised heating in Great Britain are not characterised by opposition, nor are they clearly characterised by overwhelming support. In other studies this ambivalence appears robust to change, with the proportions undecided showing little change across several years of data [18,46]. When examining the level of knowledge for each technology, relatively few respondents reported never having heard of any of the decarbonised heating technologies. However, despite this awareness a much smaller proportion reported holding any extensive knowledge of each technology. This pattern of high awareness of decarbonised heating but little substantive knowledge appears to be consistent with other UK surveys of awareness to decarbonised heating technologies [18].

The present but somewhat ambivalent support, paired with limited knowledge, may help to explain the finding that decarbonising heating is viewed as relatively less important than other means for reducing emissions. Again, consistent with previous findings [47], the heating and cooling of buildings as an industrial sector was seen as being a less important target for reducing national carbon emissions than the transport and manufacturing industries, despite these three sectors contributing a largely equivalent quantity of emissions [48]. Similarly, using domestic decarbonised heating was perceived as significantly less important compared to emission-reducing behaviours, such as using low-carbon methods of transportation or reducing general domestic energy use.

This may be attributable to several explanations. Decarbonising heating is challenging, with the practical benefits of decarbonising varying from household to household and depending on a variety of factors [9,49], and this perhaps works against any perception of heating practices as a compelling national objective for climate change. The most direct explanation is that decarbonised heating systems remain relatively less visible compared to other decarbonising sectors such as transport or industry, both of which are associated with highly salient and established technologies (e.g. electric cars) and may therefore command greater public attention. It is important to acknowledge that this limited visibility is not an essential feature of decarbonised heating technologies, and must be at least partially attributable to the lack of a coordinated and strong communications strategy from the UK government [29,50,51]. Related to this, relatively low public knowledge may also be attributable to the variety of potential technologies that currently characterise decarbonised heating. That is to say, regardless of the actual likelihood of one outcome versus another, there is no single vision of what the transition will ultimately look like and what the ‘flagship’ technology will be. Regardless, the overall consequence of this lack of visibility is that heating has yet to establish itself as a part of the ‘narrative’ of system decarbonisation in the UK.

In summary, whilst our respondents expressed support for all decarbonised heating technologies, this was tempered by a somewhat ambivalent attitude, a generally low level of knowledge for each decarbonised technology type, and a somewhat low level of perceived importance for decarbonising heating more generally.

It is important to acknowledge the potential influence of tenure when considering support for decarbonised heating or willingness to adopt specific technologies. An individual's living situation is strongly relevant when considering major changes to domestic infrastructure. For example, for homeowners the introduction of a decarbonised heating system is an elective and deliberate change to their home, whereas for renters this change is necessarily imposed. As a result, where homeowners may experience decarbonised heating as enhancing their freedom (e.g. through exercising control over their living environment and reducing bills), renters may experience this change as further restricting their control over where and how they live [52]. Similarly, whilst homeowners may adopt decarbonised heating as a security-enhancing measure to protect their home against reliance on fossil fuels. In contrast, renters may experience increase precarity, as decarbonised heating introduces uncertainties regarding disruption to living spaces and changes to existing bills or rent [9].

This dissociation could have led to our respondents having different implicit assumptions about decarbonised heating depending on their type of tenure, that in turn could have influenced our results. Designing measures that are able to cohesively assess public attitudes whilst being receptive to key individual differences is a fundamental challenge for large scale public surveying research. However, we attempted to correct for this through adjusting the item wording accordingly when assessing willingness to adopt each technology type. Furthermore, tenure type was assessed as a variable in the survey on which this study is based, and will be explored in greater detail in a future publication.

### 4.2. Comparison between technology types

Clear differences were apparent between technology types with regards to levels of support, willingness to adopt, and knowledge. Heat pumps emerged as the technology with the highest levels of all three, followed closely by hydrogen, and with district heating being markedly lower than both in all three measures. This may be attributable to variations in the clarity of the public's conception of each technology, with low understanding resulting in small differences in knowledge having an amplified influence on preferences [11,27]. For example, whilst heat pumps are relatively stereotyped in their appearance and installation, district heating systems, in the UK at least, have no archetypal description and may vary considerably depending on whether they are based on (e.g.) waste process heat or a shared residential heat source. This also likely reflects the impact of emerging preferences amongst government and energy sector actors, with policy and marketing increasingly emphasising heat pumps as the technology of choice [10].

### 4.3. Trust, responsibility and public support for policy

Our results also highlight ongoing issues with perceptions of trust and responsibility that have been consistently reported in prior research [16,53]. Respondents expressed significantly lower trust in government and energy sector actors to provide information and make decisions regarding the transition to decarbonised heating, when compared to respondents themselves or their peers. In contrast, respondents also placed significantly higher responsibility on government and energy sector actors to finance the transition, as opposed to consumers. In addition to being an extension of limited trust in these actors, this allocation of responsibility may also be attributable to a basic unwillingness for the public to invest given cost of living concerns [29]. This was perhaps reflected in our finding that when presented with different policy options for facilitating the transition to decarbonised heating, respondents expressed significantly higher support for policies involving government action (e.g. provision of subsidies), in comparison to a policy that legislated the transition through forcing a change in public behaviour (i.e. banning the sale of new oil/gas boilers). Whereas the former emphasise the responsibility of government and other executive actors, the latter emphasises the responsibility of the consumer, respectively reflecting policies that either follow or go against the grain of public perception. The public stance is therefore nuanced, emphasising both government responsibility but also the freedom to transition to decarbonised heating on their own terms, without being forced. Salite et al. [54] report similar findings, finding members of the public accepted some degree of compulsory behaviour change but did not want to feel coerced. Similarly, Butler et al. [21] highlight that the public do not view themselves as empowered market actors, and under such circumstances will prefer some regulatory control.

It should be acknowledged that other public surveying work has suggested less polarised support for decarbonised heating policies [45]. Nevertheless, these findings could herald a potential sticking point for the future progress of the transition, as they suggest public expectations run contrary to the government's conception of the transition as a market-led consumer-directed process. This could set the conditions for a ‘governance trap’, wherein the actors involved view one-another (but not themselves) as responsible for taking action [55,56].

### 4.4. Key factors influencing willingness to adopt decarbonised heating

The survey's decision pathway element attempted to build upon what was known about public attitudes to decarbonised heat by exploring key enabling factors underlying willingness to uptake heating technologies. However, our findings indicated a strongly polarised response from our respondents, with any reported changes in attitude being strongly influenced by a respondent's initial position, and less so by the actual content of the scenarios explored in the survey element. Despite this, some variation was evident between scenarios. Change in attitude in response to a scenario describing reduced running costs emerged as the most influential factor in predicting a respondent's initial position for hydrogen and heat pumps, and change in attitude in response to a supplier having a positive reputation was the most influential for district heating. However, these results represent minor exceptions from a far more salient overall trend.

Strongly held and inflexible beliefs are not in themselves remarkable. A network account of attitudes would predict that an attitude maintains stability and coherence across the network by resisting changes to strongly established associations and beliefs [31]. However, as the majority of respondents in our sample appeared to know very little about decarbonised heating technologies, and likely gained most of their understanding via the information cards they were presented with, one would not expect these attitudes to be strongly established.

This highlights that judgements regarding decarbonised heating technologies are not necessarily or solely the product of directly relevant beliefs, but rather are determined by a broader context of implicitly or indirectly related factors within the attitude network that may have been more firmly established in our respondents.

### 4.5. Network trends underlying the structure and dynamics of public attitudes

Psychometric network analysis of our dataset shed light on what these factors may be by modelling the underlying structure of the attitude object and highlighting which elements in the network are particularly influential in shaping the state of the network, and shaping key evaluative reactions (e.g. initial position of willingness to adopt decarbonised heating).

A single variable emerged as a key factor leveraging strong influence across the network constituting attitude towards decarbonised heating. This variable was 'social circle', relating to the number of individuals in a respondent's immediate social environment (e.g. family, friends) using decarbonised heating systems. This trend has been observed elsewhere relating to behavioural change and domestic energy technology. A study tracking adoption of solar photovoltaic systems in the US found uptake followed a highly clustered pattern indicative of a 'neighbour effect' [57], and social normative effects have been shown to be effective at changing energy use behaviour [58,59].

This factor was highly central in the network structure of the attitude, possessing direct connections to many other variables in the network, and bridging many indirect connections between other variables. Importantly, the centrality of this social circle factor was highly stable, and, and more central than many other variables in the network at a statistically significant magnitude. This suggests that familiarity with decarbonised heating in one's social environment both explains the relationship between many other variables in the network, but also that changes to this variable may result in substantial changes to the overall network. In terms of causal attitude network theory, this implies that coherence with one's normative social context is instrumental in maintaining stability within the attitude as a whole. This is perhaps consistent with the finding that interventions for promoting pro-environmental behaviours that emphasise social comparisons are particularly influential [60].

The central position of this social circle factor means it can also be interpreted as bridging the relationship between the various communities in the network, and in particular the community of variables representing engagement with decarbonised heating. That is to say, in addition to being an influential factor in shaping the overall network state of the attitude, this social circle factor is also highly influential in predicting the key outcome of personal intention to uptake decarbonised heating technologies.

Human social sensing has been demonstrated to be both highly accurate [61] and highly influential as a predictor of behaviour, above even explicit personal behavioural intention [62,63]. Indeed, individuals often underestimate the extent to which they are influenced by normative social forces [64], perhaps explaining why this trend emerges most saliently when examining network betweenness (i.e. an implicit network property measuring mediation between many otherwise unrelated variables).

Noteworthy is the other factor directly connected to the engagement cluster was general support for the national adoption of decarbonised heating technologies, which can be understood as a straightforward coherence between endorsement for the transition both broadly (see also [65]) and within one's own home. However, this support variable was far less central in the network than the social circle factor, suggesting that whilst support may be influential, it does not bridge influence across the network in the same fashion. Interestingly, the social circle and support factors were themselves connected by a negative edge, indicating that increasing exposure to decarbonised heating technologies in one's social environment does not lead to increased engagement through enhancing support for the transition more generally, but rather has a more direct influence of its own. It is possible that this negative connection indicates that individuals with experience of decarbonised heating technologies in their social environment are less likely to believe they are suitable for uptake in every household, despite being personally willing to uptake the technology themselves.

Investigating this possibility represents a path for future research, along with a more general investigation of the relational dynamics that underlie this social circle trend. That is to say, whilst we identify that attitudes towards decarbonised heating are shaped by an interaction between members of the public and their social environment, the precise nature of this interaction remains unclear. There are a variety of ways in which one individual may relate to another depending on their identity [66], for example the normative influence of one's neighbour is likely to be qualitatively different to the normative influence of one's parent or a close friend [8].

### 4.6. Methodological reflections

From a methodological standpoint, the study demonstrates the utility of adopting a causal network modelling approach for studying complex public attitudes datasets. In addition to providing an effective method of visualisation for top-down interpretation of the dataset, the embedded data in the network provided a rich topographical description of the structure of the dataset as an attitude object, which to the author's knowledge is the first of its size and complexity in energy research.

Whilst promising, it is important not to overinvest this result with too much confidence. A key assumption of the psychometric network modelling approach we adopted is that attitudes are highly dynamic and interrelated structures, which are constantly adjusting to maintain consistency and stability as new information is acquired. In an attitude consisting of highly certain or deeply held beliefs, these adjustments may arguably be expected to be quite minor. However, attitudes to decarbonised heating systems and other emerging technologies are based on information that is largely hypothetical or contingent on strings of assumptions and estimations. This may render the attitude modelled in our study temporally unstable and prone to larger adjustments when new information causes uncertainties to collapse into more confident beliefs. As a result, we describe an account of public attitudes that is broadly reflective of this pivotal early phase of the transition to decarbonised heating in the UK. Beyond this phase, it is possible that the particular concerns and beliefs of the public described here will grow or diminish in their significance as they follow the future trajectory of the transition. Thus, it is important that future research continues to track and explore how attitudes towards decarbonised heating technologies evolve over time.

## 5. Conclusion

Our results describe a landscape of public attitudes in Great Britain that is characterised by general awareness and support for decarbonised heating, tempered by limited knowledge, clear differences in public preference and knowledge between technologies, and a high proportion of the public appearing ambivalent in their position of support. It is important that the actors involved in facilitating the transition are aware of this clear dissociation between technology types. They may elect to 'go with the grain' of public preference, capitalising on the existing support for heat pumps and conforming with expert policy recommendations [67]. Alternatively, this dissociation may highlight the need to address the lagging support and awareness for both hydrogen heating and (in particular) district heating.

Willingness to personally adopt decarbonised heating technologies appears firmly established and relatively resistant to change. The influence of one's social circle emerged as a key factor apparently leveraging willingness, along with many other variables underlying attitudes towards decarbonised heating. This implies that normative social influence may have a greater impact on shaping public opinion than more direct influences, such as the provision of relevant information. Encouragingly, this suggests the transition to decarbonised heating may be supported by a bottom-up normative influence or 'neighbour effect' [57], that may compliment existing top-down strategies.

A simple policy conclusion, then, is that it may be beneficial to prioritise a 'boots on the ground' approach, systematically introducing clusters of decarbonised heating in selected neighbourhoods to move public opinion and encourage uptake via this normative social influence.

However, it is important to remember that influence in an undirected network is bidirectional, and so the absence of a conducive social context could negatively impact public opinion towards decarbonised heating, and facilitate resistance to behavioural change as much as it has the potential to do the opposite. This highlights the vital importance of actors involved in the transition 'getting it right on the first try', preventing a scenario in which a conspicuous absence of decarbonised heating technologies in the everyday social environment of the public becomes a barrier. Key to this is the development of thoughtful, evidence-based policy that is receptive to public preferences and ensures a positive experience for consumers making the transition.

It is also important to contextualize our findings within the emerging shape of the transition to decarbonised heating in the UK, which is very much a live and dynamic process at the time of writing. Whilst UK government policy currently still frames the transition as a market-led and consumer-driven process, this policy looks to be less realistic in practice. For example, as significant concern now exists regarding the feasibility of hydrogen as a national decarbonised heating option [13], heat pumps are now likely to be the most suitable technology for the majority of UK households.

As a result, whilst consumers will likely retain autonomy over when they decarbonise their heating systems, they may ultimately have little choice in how they decarbonise. However, this does not mean public attitudes are unimportant. Limiting this choice may provoke a strong public response, with freedom of choice previously identified by members of the public as a key element of the decarbonisation transition [65,68].

More broadly, whilst preferences between technologies may ultimately prove less relevant in practice, these preferences nevertheless reflect values and beliefs about what a heating system should be [69], that will remain influential irrespective of the specific technology type that is eventually adopted. Ensuring that policy follows the grain of public values and expectations could be key to avoiding a protracted and problematic transition to decarbonised heating.

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## CRediT authorship contribution statement

**William Smith:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Christina Demski:** Writing – review & editing, Supervision, Conceptualization. **Nicholas Pidgeon:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## 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.

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## Data availability

Data will be made available on request.

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