Technology in Society 77 (2024) 102508

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Assessing the adoption of sustainable heating technologies in the United Kingdom – A case study of socioeconomically deprived neighbourhoods of Nottingham city

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ARTICLE INFO

Keywords:
Sustainable heating
Low-carbon society
Behavioural changes
Technology acceptance
Technology adoption
Climate change

ABSTRACT

The transition to sustainable heating technologies is crucial to reduce greenhouse gas emissions, mitigate the impacts of climate change and enable a sustainable and low-carbon society. However, a successful transition will require transformative, and large-scale household behavioural changes, and their acceptance and adoption of new technologies. Through mixed data collected at household level (n = 70) in three of the 10 poorest areas of the UK city of Nottingham (Aspley, Clifton, and St Ann's) we deepen the understanding of people's engagement with their current heating systems, their heating preferences, and views on adopting sustainable heating systems in the future. We find that despite the price increase in fossil fuel-based heating and people's reduction in heating use to reduce costs, getting them to move away from their current systems is very challenging, as most people are unwilling (41.13%) or sceptical (23.01%) about it as these systems are familiar, and generally perceived as more affordable, cost effective and efficient. Moreover, most people (71.43%) are unaware of the government's heating transition plans, but they believe that the adoption of sustainable heating systems should be optional to allow them to evaluate the pros and cons of the systems, and to choose the one that is better for them, that they can afford. Prompting a shift will need more than the common type of financial incentive. There must be first the provision of non-financial incentives to reduce some of the sociotechnical and perceptual barriers to adoption and motivate people to accept and engage in heat decarbonisation as part of a moral responsibility to the environment, and towards current and future generations.

1. Introduction

The decarbonisation of heating through the adoption of sustainable heating technologies is vital to lower greenhouse gas emissions (GHG), and the effects of climate change and enable societies to be sustainable and low carbon. Heat accounts for more than 50% of global energy use and around 40% of global energy-related carbon dioxide emissions [1]. The current energy price and climate crises that have been verified around the world make this transition more urgent. Governments have a unique role to act in this regard to dramatically scale-up the transition, while addressing the three elements of the energy trilemma (energy security, affordability, and environmental sustainability). Government can provide tactical vision, policies, and incentives that can stimulate private investment, innovation and adoption [2]. Several governments worldwide have set robust and ambitious goals for heat decarbonisation and ensure their energy security through a mix of supply- and demand-side options [3]. However, the former has generally received more attention than the latter options [2].

The development of sustainable heating technologies such as heat pumps (HP) and district heating (DH) is expected to play a key role in the reduction of CO2 emissions in buildings, particularly in parts of the world where the demand for heating is higher, such as in Europe. However, a successful transition will require potentially transformative changes not only in technologies but also in human behaviour and preferences [2,3]. Household behaviour and their collective consumption are responsible for around 72% of global GHG emissions [3]. With fossil fuel-based heat demand expected to increase over the next few decades, large-scale behavioural changes such as reducing energy

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https://doi.org/10.1016/j.techsoc.2024.102508
Received 21 November 2023; Received in revised form 3 March 2024; Accepted 9 March 2024
Available online 15 March 2024

demand, altering patterns of consumption, and changing lifestyles to reduce carbon footprints is a key pathway towards the transition to a low-carbon society [2,3]. Households acceptance and adoption of sustainable heating technologies is vital to reduce their heating demand and carbon footprints. As such, understanding people's current engagement with their existing heating systems, and their perceptions of and willingness to adopt low-carbon heating is a crucial starting point [4], but very challenging. This paper, therefore, aims to assess the status quo to deepen this understanding by taking the case of the UK city of Nottingham. The paper builds on the increasing research on sustainability transitions that highlights the crucial need to put households at the centre of the transition due to the pivotal role they play as drivers of innovation, diffusion, and adoption (see, e.g., Refs. [3–7]).

Despite the availability of the technologies, and in many cases, their economic benefits, there are other barriers that prevent their widespread adoption [8]. For decades researchers have investigated what drives human behaviours in the adoption of new technologies and have looked at a range of factors such as social demographics (e.g., Refs. [5,9]), economic factors (e.g., Refs. [10,11]) and awareness (e.g., Refs. [12,13]). However, having a comprehensive overview of the broad range of factors that influence their behaviours is a daunting task since the factors vary across different types of technologies, households, and geographic areas [8]. Schot et al. [7] argue that consumer behaviour goes beyond always making rational conscious decisions as their decisions are largely shaped by shared routines embedded in socio-technical systems, involving considerable symbolic, practical, and cognitive actions beyond the initial buying decision. Since most decisions involve a certain degree of uncertainty; thus, such work help consumers form their expectations about the possible outcomes of different courses of action, which might help them to decide, and hence give direction to their behaviour [14].

Decision-making can technically be defined as the act of choosing the course of action that is expected to be the best from a group of alternatives [15]. While behavioural decision making "endeavours to understand the actual influences on actors in making choices" [16, p. 519]. Thus, we draw upon behavioural decision theory to untangle factors that influence people's subjective judgments, expectations, intentions, decision making, and behaviour towards the adoption of sustainable heating technologies in the UK. The UK is a critical case study as, despite some progress over recent years, the use of sustainable heating technologies remains very low at 3% [17]. The UK government is the making the decarbonisation of heating a key priority to achieve Net Zero by 2050 as heating represents a significant portion of energy demand and consumers' income spending. The high demand (around 40%) is responsible for over a third of GHG emissions as heating is mostly fossil fuel-based, being natural gas the main energy source [18]. Sustainable heating technologies such as heat pumps (HP) and district heating (DH) are the main technologies acknowledged and supported by the government to decarbonise the heating sector and achieve its clean growth objectives.

The UK government has developed a range of policies, regulations, long-term targets, and initiatives to scale-up the deployment and adoption of these technologies. However, there is an increasingly uncertainty about optimal heat decarbonisation policies and pathways to decarbonisation as well as NetZero commitments. The existing discussions appear messy and affected by interests from incumbents in the sector that are promoting decarbonisation pathways that maintain a gas-based system, despite the existence of other sustainable technological pathways [19]. The recent announcement made by the UK prime minister about the government's intention to weaken some key green commitments, including delaying the phase out of gas boilers by 2035, is a major example of the power of incumbents' interests, despite claims that it intends to save households money by giving them more time to freely make the transition to HP.

Within this context, we analyse the challenges of decarbonising heat at household level in Nottingham, UK. This analysis was part of a wider study of decarbonising heating in Nottingham and enabled us to profit from insights of key local stakeholders in designing the research. The city provides a highly relevant context to explore the use and adoption of sustainable heating systems since the city has the largest DH network (68 km of insulated pipework) in the UK, which has been providing heat and hot water for 5000 dwellings and over 100 commercial premises for three decades [20]. We first provide an overview of the range of factors identified in the literature that influence individuals' decisions to adopt new technologies and measures that could help overcome some barriers to adoption in order to scale-up the development and uptake of these technologies. We then turn to the findings to explore and discuss about participants current heating systems, and they level of attachment to the systems as well as their awareness and perceptions of and willingness to sustainable heating systems. We also explore and discuss their awareness of the UK government heating transition plans and whether or not they think the plans should be enforced or optional. This is followed by some concluding remarks of the study.

2. Theoretical background

For decades researchers have been extensively trying to understand how people actually make decisions, and this has resulted in the formulation of many theories to explain the process, including the Behavioural decision theory. The theory suggests that the decision-making process is highly situation-dependent, i.e., it varies according to the characteristics and amount of knowledge that the decision-maker has about their surrounding environment [15]. It also leads to the development of various psychological processes, involving an automatic and controlled (regulated based on thoughts) process that is performed half unconsciously and consciously, respectively [15]. Moreover, some decisions are made under certainty (when the result of selecting an alternative is certainly determined), others under risk (occurs with known probability as the result of selecting an alternative) or uncertainty (when the probability of the result of selecting an alternative unknown) [15]. Despite these different circumstances, making the best decision when faced with various alternatives, preferences and factors can become somewhat challenging, as is the case of heat decarbonisation.

Despite the pressing need to decarbonise domestic heating, getting households to switch to sustainable heating systems is difficult [21]. The switch is not simply an economic investment decision and adoption process, but a complex sociotechnical process that involves not only technological and infrastructural changes but also reconfigurations of indoor domestic regime, social practices, culture, and political, regulatory, and institutional framework [6,21]. It also involves motivations to adopt a new technology, attitudes, beliefs and behaviours towards it, installation hassles, the level of comfort before and after installation and choices available in the market [22,23]. Such complexities make households resistant to change and thus, making the heating sector one of most difficult to decarbonise [24]. Households have multiples goals to achieve with heat, being thermal comfort the most important one [25]. However, saving money and minimising the impacts on the environment and climate [25] are also some of the goals that have increasingly become important to households in the current days due to high energy prices and cost of living, and climate crisis.

Sustainable heating systems offer plenty of opportunity to address these constraints due to their efficiency and sustainability. However, the upfront costs of the technologies have been a major concern to households, developers and building owners and significant financial barriers to their uptake [2,26]. A 2022 BEIS's report on decarbonising heat in homes in UK found that developers may prioritise the installation of technologies that require low investment as the building owners are responsible for running costs [17]. Yet some building owners also have no or low interest in high installation costs as the benefits of technologies would accrue end-users of the building, who might be different [10]. Consumers often lack the power to significantly change the existing socio-technical regime [27]. These investment constraints have

also limited improvement in the energy efficiency of building envelopes.

Thus, providing financial (e.g., subsidies and low-interest rate loans) and non-financial (e.g., polices, regulations, information dissemination) incentives is essential to address the upfront costs and boost investment in the development and adoption of the technologies [2,12]. The UK government is currently providing a subsidy of £5000 to consumers to help them pay for and reduce the installation costs of HP, but the adoption rate fallen short of what is necessary. Uptake of the subsidy has been low due to, among other factors, inadequate promotion of the scheme, very low public awareness of sustainable heating systems and very high upfront costs of HPs, even with the subsidy [28].

Information dissemination is vital to raise consumers' awareness of new technologies and their socioeconomic and environmental benefits, while at the same time reducing their uncertainty regarding new technologies and incentivizing them to freely have a pro-environmental behaviour and adopt the technologies [12,13]. Information dissemination (e.g., advertising campaigns) plays an important part at the adoption stage since it helps to reduce consumers uncertainty regarding new technologies and to persuade/encourage them to adopt it [13]. Rogers [29] considers awareness and understanding of an innovation as the first stage in the innovation adoption process model, followed by persuasion (when an individual form a favourable or unfavourable attitude towards it), decision to adopt it or not, implementation of their decision (put the innovation into use) and confirmation (reinforcement of their decision). Additionally, Takemura [15] identify 5 more stages during the decision-making process, including the formation of preference and choice (see Fig. 1).

Although more attention has been given to the infrastructure development, consumers are essential part of the whole transition process. Consumers contribute to the emergence, development (including patterns of use, modification, and improvement), legitimacy and diffusion of niche technologies [12,27]. Specifically, for the transition to sustainable energy, consumers can also contribute to the production and distribution of renewable energy (e.g., wind and solar) and low-carbon heating (e.g., communal or district heating) for their own use, and share and sell the excess energy generated to other users in the community [30]. This way, these "prosumers" (producers and consumers) can create a supply-demand equilibrium through the share of energy – a process known as peer-to-peer (P2P) energy trading [30]. Thus, inclusive and people-centred approaches in the transition are crucial to speed-up the transition, while at the same time allowing vulnerable communities to manage the high upfront costs of these technologies and ensure that the benefits of transitions are felt widely across societies [2].

Schot et al. [7, p.1] argue that "current government information policies and market-based instruments aimed at influencing the energy choices of consumers often ignore the fact that consumer behaviour is not fully reducible to individuals making rational conscious decisions all the time". Consumers' choice for their heating systems and energy demand is shaped by both economic factors (e.g., cost and income), and non-economic factors. The latter may involve cognitive (e.g., subjective norms, attitudes, and perceived controls), physical (e.g., house characteristics) and/or legal constraints (e.g., ownership status, regulations, and legislation) [26,31]. Households' sociodemographic characteristics and their peers (e.g., family members, friends, and neighbours) also influence their awareness and perceptions of new technologies, their attitude towards it and willingness to adopt it [5,9]. Consumers' peers often share their knowledge and//or experience about new technologies and provide their persuasive (favourable or unfavourable) perceptions of the technologies and recommendations about the adoption [9].

Thus, those segments of people that are usually more open to innovation often serve as tactically key target groups for marketers and policymakers to boost its diffusion [5]. All in all, a broader understanding of consumers' behaviours as individual, collective, economic, social, political, and cultural, and drivers of adoption offers opportunities for more transformative and inclusive changes across society [23]. Those changes will be vital to overcome the existing obvious and hidden barriers to the successful development and uptake of sustainable heating systems and other green technologies.

3. Methodology

3.1. Study area

The UK has a total of 23.8 million households in England, occupied by its owners (62.5%), private renters (20.3%), social renters (17.1%) and rent free (0.1%) [32]. The latter is an important part of the national housing story and an essential part of the history and identity of the selected study location (Nottingham City) there is a substantial social housing sector [33]. Social housing is accommodation provided by local authorities or registered providers such as housing associations to rent below market level rents or to buy through schemes such as shared ownership [34].

Around 25.5% of the Nottingham city population of 323,600 people lives in social houses, placing the city in the highest 10% of English local authority areas for the share of households living in social houses [34]. Around 11.7% of the population is over 65 years old [32]. Moreover, roughly 20.6% of the city households are fuel poor [35] and 48.7% of the population aged 16 years and over is employed, 5.3% is unemployed and 46% is economically inactive [32]. The latter is mostly due to retirement (13.4%), long-term sickness or disability (5.5%), home or family care responsibilities (5.4%), studies (17.9%) and others (3.8%) [32]. The city was ranked as the poorest in Britain based on gross disposable household income (GDHI), which is i.e., the amount of money all the household members earn after taking into account tax and benefits [36].

Thus, based on the GDHI and the heating system in use, we selected three of the 10 poorest areas in Nottingham, namely Aspley, Clifton, and St Ann's (see Fig. 2). Aspley, ranked the poorest, has average earnings of £20,900, while St Ann's (the 7th poorest) and Clifton (the 9th poorest) have average earnings of £22,200 and £24,300, respectively, which are well below the average earning of the city's top 10 richest areas of between £28,800 and £57,200 [36]. Aspley and Clifton are mostly fossil fuel-based heating areas, while St Ann's is mainly connected to a DH system that produces heat through incineration of municipal waste. Around 57% of the participants of this study live in social houses, 21.5% in private rented and the remaining 21.5% owned the property (see Table 1).

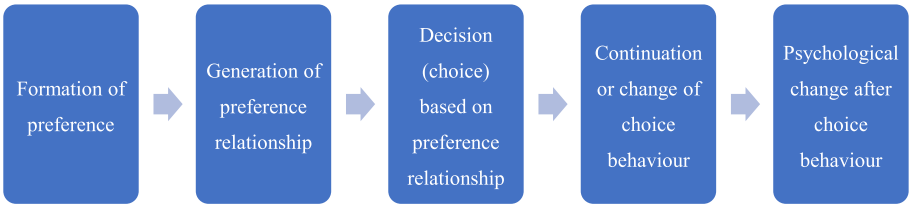

Fig. 1. Stages of the decision-making process (source: adapted from Ref. [15]).

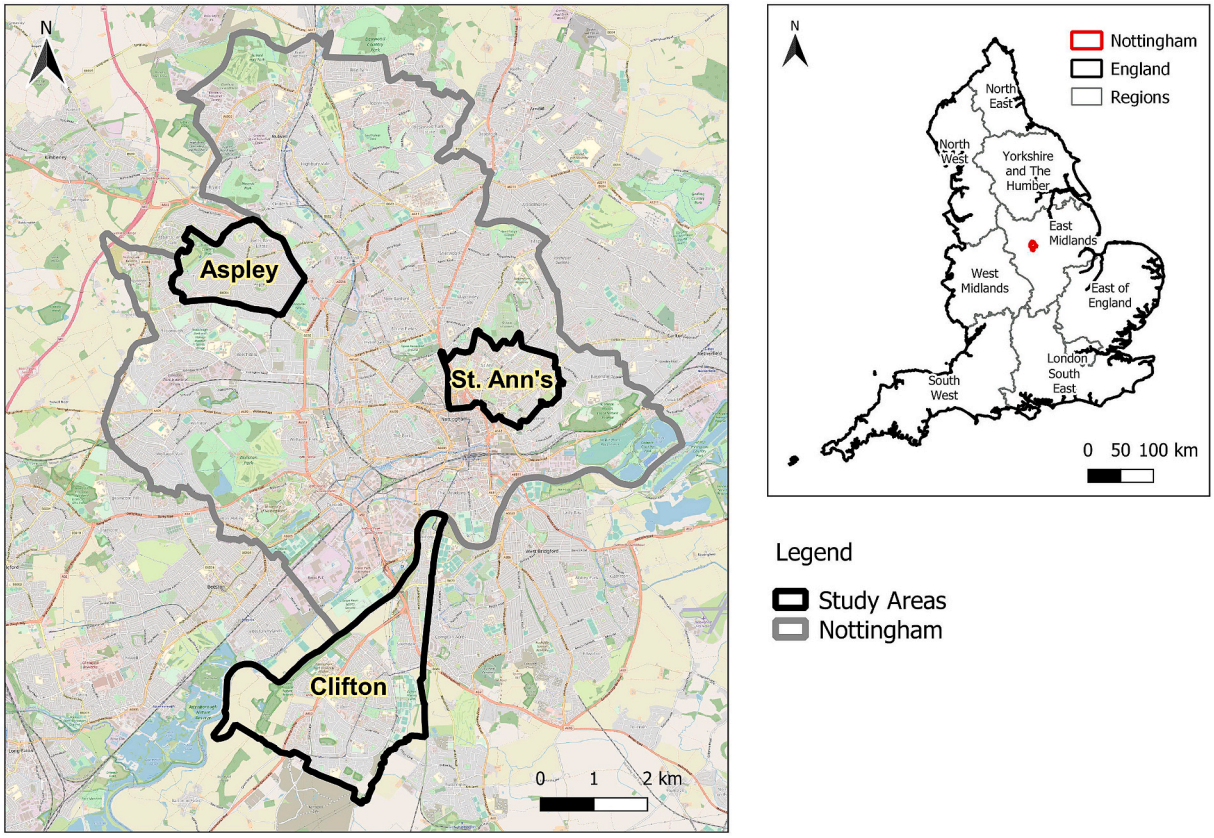

Fig. 2. Location of the study area (source: authors, 2023).

Table 1
Number of participants of the study according to sociodemographic characteristics and heating system in use.

Characteristics		Aspley	Clifton	St Ann's	Total	Percentage (%)
Gender	Female	14	16	14	44	62.86
	Male	9	7	10	26	37.14
Age group (years old)	<21	0	1	0	1	1.43
	21–40	9	12	7	28	40.00
	41–60	7	3	9	19	27.14
	>60	7	7	8	22	31.43
Education level	GSCE	0	0	1	1	1.43
	Some university	2	5	1	8	11.43
	Bachelor	1	0	0	1	1.43
	Masters	3	0	2	5	7.14
	Doctorate	1	0	0	1	1.43
	Others	16	18	20	54	77.14
Occupation	Employed	10	7	6	23	32.86
	Unemployed	7	5	10	22	31.43
	Retired	5	6	7	18	25.71
	Student	1	5	1	7	10.00
Housing situation	Owner-occupied	7	5	3	15	21.43
	Private-rented	6	7	2	15	21.43
	Social housing	10	11	19	40	57.14
Type of heating system used	District heating	0	0	21	21	30.00
	Gas-based heating	21	23	2	46	65.71
	Electric heating	1	0	1	2	2.86
	Solid fuels	1	0	0	1	1.43

3.2. Methods

The study was conducted between April and June 2023 and a total of 70 people at household level were interviewed in the three neighbourhoods. Interviewees were purposively selected based on their location and socioeconomic characteristics. In cases where the selected interviewees were unavailable, we reverted to a random sample to replace them with their available neighbours. This randomisation was one of the reasons we did not manage to achieve a gender balanced number of participants, resulting in women constituting most of the participants (see Table 1). This also resulted in a high proportion of unemployed and retired interviewees. The fact that a considerable number of people are working from home since the COVID-19 pandemic also made most of the potential interviewees busy and unavailable for the interview. These availability issues, along with the purposive nature of the study and the data saturation, led to the modest number of study participants.

However, the data collected was enough to allow the broad and deep understanding of the topic under study. Moreover, the modest sample size and semi-structured/open-ended questions allowed the collection of more detailed data from each participant.

The semi-structured interviews with individuals intended to comprehensively explore how social embeddedness, sociodemographic, economic, and geographic factors shape their subjective judgements, expectations, intentions, and (conscious and unconscious) decisions to adopt new heating technologies. The qualitative data were transcribed and coded in NVIVO using thematic analysis to better capture, interpret and analyse participants responses, while the quantitative data were coded in excel and analysed in SPSS, mainly for descriptive cross-tabulation analysis.

4. Results and discussion

4.1. Participants' current heating system

As a starting point, we asked participants about the type of heating system they use in their properties, if they chose it and for how long they had been using it. Similar to the rest of the UK, gas-based heating is the main type of heating system used in the study sites by around 65% of the participants (see Fig. 3). All participants in Clifton and around 91% of participants in Aspley use gas-based heating, which the majority (91.4%) found installed in their properties. The 8.5% of participants who chose to install gas-based heating system did so based on their preferences and familiarity for and affordability and efficiency of this type of systems.

The general sense was that gas-heating system is better than electric for being more cost effective and efficient, including the capacity to retain the heat in a room for longer after turning it off. Despite this perceived cost effectiveness, the current rise in energy price and cost of living meant that affordability also became an issue to gas-based heating, leading people to have to significantly reduced the amount of time they use their heating systems as a way to reduce costs, as exemplified below by these two (under 40 years old) females from Aspley and Clifton:

> "I only turn the heater on when it's really cold and only in the room I am in, but just enough to heat up the room, which is between 30 and 60 minutes. I keep my dressing gown on to keep me warm as I rarely turn the heat on for more than once a day (interview Nttg_Aspley_22, May 2023).

> "I put the heater on for 2 minutes and then I'm already on emergency and because of that, I have to turn the heater off. I'm on pre-paid meter and the money goes up so quickly. I budget a certain amount of money for gas and electric, so when the money is gone, it's gone (interview Nttg_Clifton_015, May 2023).

Indeed, the IEA [2] reported that the energy price crisis caused a massive wealth transfer from consumers to producers, resulting in consumers having to find alternatives to reduce their energy bills such as by increasing their demand for oil and coal. These alternatives were unusual among the interviewees since only two interviewees (2.86%) who are living in council rented properties are using unusual heating sources for urban areas as their preferred heating systems due to affordability issues. A retired 73 years' old male from Aspley is currently using solid fuels only, despite having partial gas central heating in his property, arguing that "*I don't think solid fuels are bad for my life, I've used it all my life. I like and prefer it. It is a nicer heater and now it's cheaper than gas. I get one deliver a year and that's it, it does me*".[1] Another 47 years' old unemployed male who lives with his wife and 5 children under 8 years old in St Ann's shared that they are using gas canister-based heating, despite being connected to DH, because they find it cheap, very nice and safe, allowing them to buy only one gas canister during winter for £45, which lasts for 3–4 months after opening it for just 1 h daily, enough to keep their flat all warm as they also benefit from the warm from their neighbour's similar gas bottle heating machine.[2]

On the other hand, only 11.4% of participants complained about efficiency of gas-based heating because their system does not function properly or takes longer to start heating up, which some attributed to the old radiators and others to old gas boilers, rather than the system itself. The use of sustainable heating systems remains low in Nottingham, limited mostly to people living in St Ann's area. Thus, 30% of the participants of this study participants are using DH as their heating source. The decision to connect to DH was made by the council upon the development of the network around 40 years ago. This is probably the reason why 4.29% of participants who are not living in council-owned properties managed to change their heating system to gas-based (2.86%) and electric (1.43%) more than a decade ago. Some participants shared that currently they are not allowed to disconnect from their DH even if they own the property.

4.2. Awareness and perceptions of sustainable heating systems

When we asked participants if they were aware of any heating systems that are considered sustainable, the majority of them were not aware of any (59%), while around 37.16% were aware of some and 4.29% probably aware of some. When looking at their responses by area and the type of heating source used, most (54.35%) of participants in Aspley and Clifton, which are fossil fuel-based heating areas, were not aware of the systems and around 39% of participants were aware and 6.52% were probably aware of a system. Participants were mostly aware of HP (61.11%), with only 16.67% (3) aware of DH, and 16.67% aware of both DH and HP. In fact, despite the DH system being run in the city for over 40 years, awareness of DH was only verified among participants who had family members or friends living in St Ann's since they shared about their experiences with the systems. This shows the important role of peers on information dissemination about a technology and their experience and (favourable or unfavourable) perception of it, as pointed out by Michelsen and Madlener [9].

While participants living in the DH area of St Ann's were mostly (66.67%) not aware of any other sustainable heating systems besides the DH that runs in the area, being the remaining 33.33% entirely aware of HP. In fact, HP is currently gaining more attention from the UK government, news and media sources compared to DH that is mostly forgotten in the debates about replacement for gas boilers, leading to HP being referred as the most preferred replacement. The government delay in the creation and development of the heat network zoning (planned to be introduced by 2025) aiming to connect certain buildings to DH might be influencing the debates.

In general, as shown in Fig. 4a, under 40-year-old participants were the ones less aware of sustainable heating systems but were as equally aware of these systems as participants aged between 41 and 60 years old, while most over 60 years old participants did not have knowledge of these systems. On the other hand, as shown in Fig. 4b, education level did not seem to significantly influence the level of participants' awareness of sustainable heating systems as participants with other types of education level (e.g., certificate, diploma and apprenticeship) which was mostly professional) were the ones who were most, least and probably aware of these systems, making it hard to link education level with their level of awareness of these systems. People with other types of education represented most of the interviews, which was also a reflection of the sociodemographic situation of the city. The 2021 population census showed that Nottingham has around 49.2% of people with below Level 4 and above qualification (higher national Certificate or diploma,

[1] Interview Nttg_Aspley_007, May 2023.

[2] Interview Nttg_St_022, April 2023.

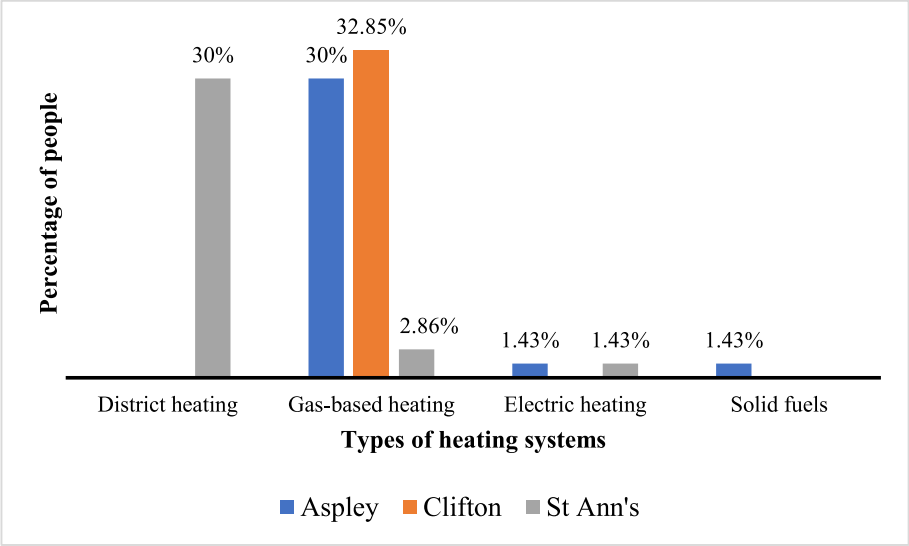

Fig. 3. Types of heating systems in use in the study site.

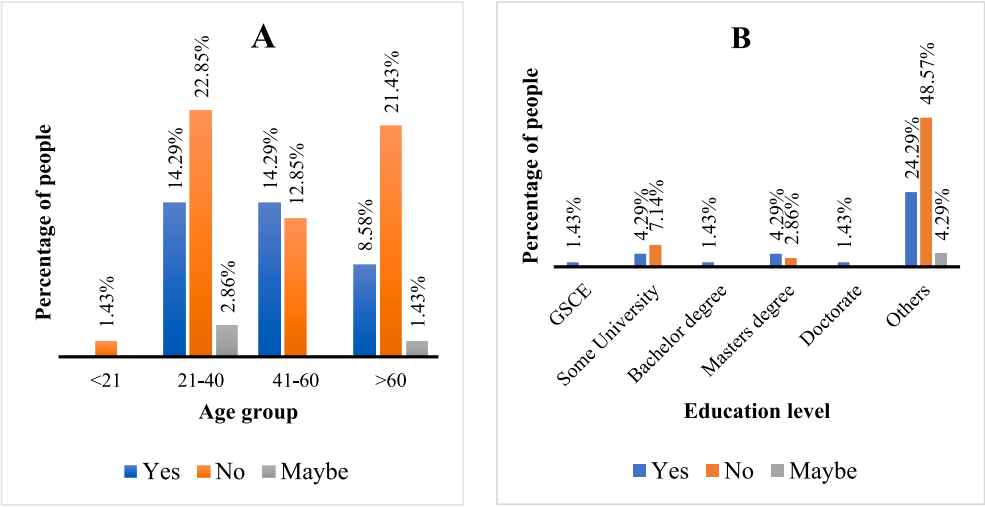

Fig. 4. Percentage of people who are aware of sustainable heating systems, according to their age and education level.

bachelor's degree, or post-graduate qualifications), 2.7% with qualification of unknown level, 19.5% with no qualification, and 16.1% (aged between 18 and 30 years old) full-time students [37]. Moreover, there was a slight balance between the number of participants with some or full university degree that were and not aware of the systems. These results reflect the general low levels of awareness of sustainable heating technologies across the UK, especially among people living on-grid areas or using electricity for heating since people on off-gas grid are more likely to know about HP [38].

Nonetheless, most participants (69.58%) in Aspley and Clifton had no perceptions of sustainable heating systems since they did not have much knowledge about the specifics of the systems in terms of efficiency and running costs. While around 10.86% had positive perceptions of the systems as they believed that these systems have the potential to address environmental and affordability issues that is currently verified with fossil fuel-based heating. Other 13.04% of these participants had negative perceptions of DH and HP due to its running costs (considered high) and efficiency issues, as exemplified by two participants from Clifton:

> "DH is absolutely no; it is a con and conspiracy! I have a 74 years' old elderly lady with cancer, and she has a £1600 bill. These are old people and she's now freaking and having to pay for it every week to try and get out somehow. They are taking their rubbish and burning it and charging them back at a non-competitive and high rate (50 years old unemployed female, interview Nttg_Clifton_023, June 2023)."

> "Heat pump is not going to be as good as my gas-based heating in any way. If the government thinks that I am going to get cold because of their lack of planning or forward planning, they can forget because I am not going to do it. They are not going to getting me swope my gas boiler which warms me and keep me nice and jolly warm (70 years old retired male, interview Nttg_Clifton_020, June 2023)."

A high DH outstanding bill of around £2000 was also reported by the 47 years' old unemployed male from St Ann's who is using gas canister-based heating, despite not using DH for over a decade.[3] While the DH heat supplier (Enviroenergy) uses a pre-paid system which, according to participants, allows them to top-up to a maximum of £200 m, the unpaid daily standing charge led to the above debts and to other participants to complain about the charge that is perceived as high. A 34 years' old

[3] Interview Nttg_St_022, April 2023.

female part-time worker and student explained that: "*once I was on holiday away for two weeks and I left £15 on the meter. They said that they charge 28 pence (p) a day for the standing charges but when I came back my meter was negative (£-4.80). Even if I had stayed for 30 days, it would have been enough. So, it has nothing to do with cheap, isn't it? That's my personal experience but my niece also had a similar issue*".[4] Participants had different awareness about the standing charge, ranging from 28p to 58p, while a recent Enviroenergy newsletter [39] refers to a tariff increase from £0.3226p to £0.3572 from 01st January 2023. These differences must be a result of the pre-paid system, which leads to the lack of a detailed monthly bill with information about the tariffs, usage and how the costs are calculated. Participants explained that they only receive an annual bill that is not meant to be paid as they have already pre-paid for their heating but to explain what consumers should be paying, what discounts they get (including for single occupants). In their market study of the domestic heat networks sector, Fu and Abbassian [40] found that heat networks consumers wanted to have better billing and tariffs information to that they are well informed in case they wish to query about what they are being charged. Nonetheless, Li et al. [41] argue that the monopolistic nature of the DH networks allows companies to profit but tend to increase costs for consumers. The continuous increase in DH costs makes it challenging to further improve efficiency, reduce cost, and enhance profitability [41].

While for HPs, users are mostly satisfied with their positive experiences due to reasons such as running costs, efficiency, and environmental benefits, but there are still some dissatisfaction and concerns regarding faulty HPs or the quality of the installation which leads some users to experience frequent issues (e.g., pressure drops, blockages, and break downs) resulting in an increase in running costs [42]. Such efficiency concerns are also verified among non-users of HP as the above example of the 70 years old retired male participant who despite not having enough knowledge of HP and not knowing a HP user, his scepticism about the new and unknown technology along with his disappointment with the current government led him to have a negative perception. He perceived the switch to HP as people accepting a less efficient and less good quality service because the government mismanaged the energy supply system with their sensible policies in the same way they did with the food system that led to the proliferation of food banks.[5] This viewpoint about the government capacity shows the importance of trust in the agent of change in influencing people's decision to accept and adopt an innovation.

Indeed, trust in municipalities in DH implementation has been one of the main reasons for the successful development of DH in Denmark and Sweden – a model that the Netherlands aims to replicate to safeguard public interests such as affordability, security of supply, and sustainability could be better safeguarded [43]. While the billing and technical issues emphasise the importance of the price model and installation process in shaping users' perception of and attitudes towards new heating systems [44]. This also emphasises the need to make extensive investment in business models and technical training and job opportunities to improve transparency and efficiency in price setting and increase the number of skilled workers and to raise people's interest in having the required training to fulfil these job opportunities, respectively [45].

Only 6.52% of interviewees had mixed (both negative and positive) perceptions about sustainable heating systems. Some people view DH as cheaper than gas but are unsure to what extent burning rubbish for heat generation is sustainable. In fact, there has been a continuous debate on this issue since, despite the benefits of reducing the volume of waste in landfills, some scholars argue that the incineration of waste may have unintentional environmental impacts due to the amount of carbon on the waste, the energy produced and wasted during the process. Other interviewees view HP as "having the potential to *help to address affordability issues in long-term, but because they are expensive systems, offsetting the purchase and installation costs is a major challenge.*[6]" Most participants in St Ann's (54.17%) did not have any perceptions about other sustainable heating system than DH. Most of these participants were happy with DH due to its affordability, as explaining by 70 years' old female:

> "DH is not expensive, it's cheaper than gas and electric, and because of the price, you manage to have your heater on all the time. So, if these other low-carbon systems are as cheap as DH, then they will help to address (gas and electric) affordability issues (interview Nttg_St_009, April 2023)".

Affordability along with efficiency is also the reason why 16.7% of participants were unhappy with DH, leading a 37 years' old self-employed female participant to comment the following: *"DH is expensive and doesn't help me when it's cold. I need to heat up my flat. I am sacrificing my health and that does not seem right. My radiators don't even fully heat up in every room. So, when it's cold, I have to heat up water bottles, I have to wrap up with layers of clothes. And for what? I am paying for something that is not really that beneficial"*.[7] Most of these unhappy participants complained about the poor efficiency of their radiators, which they described as being as old as their DH system since they were installed when the system started running in the area and have never been replaced by the council despite the obvious need. Some participants compared the great efficiency of the new radiators at their peers' properties to their old ones. However, different from participants who complained about the efficiency of their gas-based heating, the DH users were unable to dissociate their radiators issues from the DH system, which led them to primary blame the DH system before mentioning about their radiators.

In contrast all participants were aware of solar panels, and they often tended to include them as an example of sustainable heating system. This awareness is a result of the Nottingham City Council (NCC)'s widespread installation of solar panels on over 4000 social housing properties in the city boundaries since 2012 [46]. Nonetheless, there has been a mixed customers' experience with DH in the UK due to some poorly performing and inefficient systems and billing issues [47]. Most DH in UK are third generation, with high heat supply temperature of below 100 °C, which results in higher heat losses during transmission leading to inefficiencies [47]. Moreover, most DH systems are still powered by gas through Combined Heat and Power (CHP) systems, meaning that besides the need to improve the efficiency, there is also a need to decarbonise the existing systems. Nevertheless, there have been some technological advances being made by researchers to improve the efficiency, stability, and sustainability of the systems and to manage the heat supply to meet the variable heat demand such as the thermochemical energy storage (TES) system with fluidized-bed reactors [48], which is also being prototyped by researchers at the University of Nottingham in the UK.[8]

4.3. Adoption of sustainable heating systems

We asked participants if they would consider switching from fossil fuel-based or DH to (other) sustainable heating systems, the majority of them (41.13%) responded negatively, around 35.87% responded positively and 23.01% were sceptical about it. In general, as seen in Fig. 5a, participants aged under 40 were both the ones most willing (20%) and sceptical (11.43%) to consider adopting the systems, while participants aged between 41 and 60 and over 60 years old were the second (10%) and least willing (4.29%) to consider it. The latter group stated their age

[4] Interview Nttg_St_007, April 2023.
[5] Interview Nttg_Clifton_020, June 2023.
[6] Interview Nttg_Aspley_014, May 2023.
[7] Interview Nttg_St_Ann's_011, April 2023.
[8] See the explanation of the prototype here: https://www.nottingham.ac.uk/research/groups/projectvttess/.

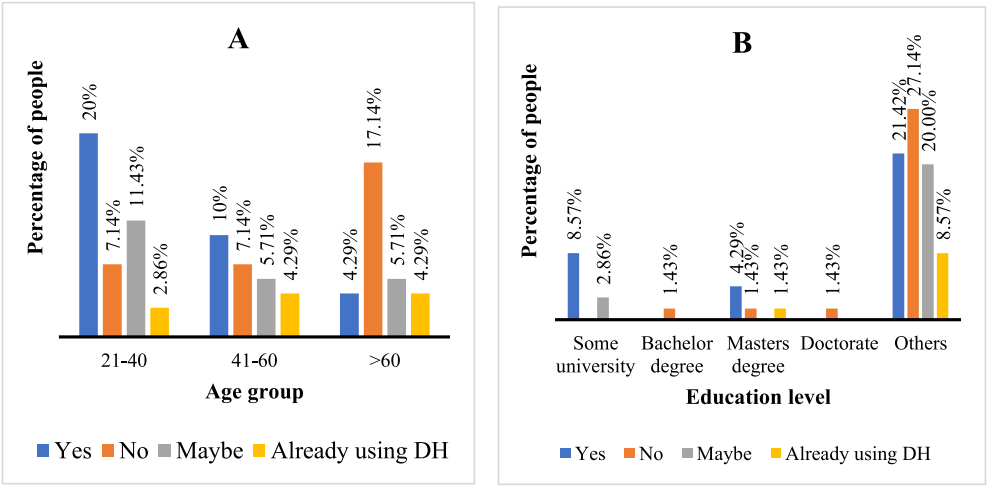

Fig. 5. Percentage of people who would consider adopting sustainable heating systems, according to their age and education level.

as the reason behind their answer, arguing that besides being too much of a trouble to install a new system, it would take years to pay itself back and because of their age, it would not be financially viable. In fact, Mahapatra and Gustavsson [49]'s analysis of the diffusion patterns of innovative residential heating systems in Sweden revealed that householder's planning to install a new heating system decreased with their age, with older householders less likely to plan it as they did not expect to have a return of their investment while they are still living in the house.

Education level also did not seem to significantly influence people's willingness to consider the adoption of sustainable heating systems as participants without a university degree were the ones who mostly showed all types of attitudes towards, i.e., they were the ones who were most and least willing to consider it, as well as in doubt about it (see Fig. 5b). Most of the interviewees of the study (77.14%) belonged to this group of people without a university degree, and as previously explained, they were also the ones who were the most, least, and probably aware of these systems. In fact, this shows the importance of increasing the dissemination of information regarding sustainable heating technologies across all sections of society. As states by Rogers [29], awareness and understanding of an innovation is the first stage in the adoption process.

Considering that some participants are already connected to a sustainable heating system (DH), when looking at their willingness to adopt these systems by area, as shown in Fig. 6a, 30.43% of participants from Aspley would consider switching to sustainable heating systems citing affordability as their only reason. While 52.17% of interviewees from Clifton would consider the switch mainly due to affordability, followed by sustainability and other reasons. The former two reasons along with efficiency issues are also what would make 25% of interviewees from St Ann's consider switching from DH to other types of sustainable systems such as HP. Efficiency issues was only cited by interviewees from St Ann's, particularly from those who complained about their DH systems not functioning well enough or taking too long to heat up their properties. Nonetheless, Nesta (an UK's innovation agency for social good) reported seeing some indications that demand for HP installations is beginning to increase in UK as their recent research suggested that more than 1 in 10 homeowners would choose a HP over a new gas boiler, even before receiving government subsidies [50]. Yet, the demand for HP and the number of HP installations remains low compared to gas boiler (ibid) and compared to other European countries. In 2022, the UK was the least contributor to Europe's HP sales growth of almost 38%, having sold the least amount of HP, only 55,168 units out of a total of 3 million units sold across Europe [51].

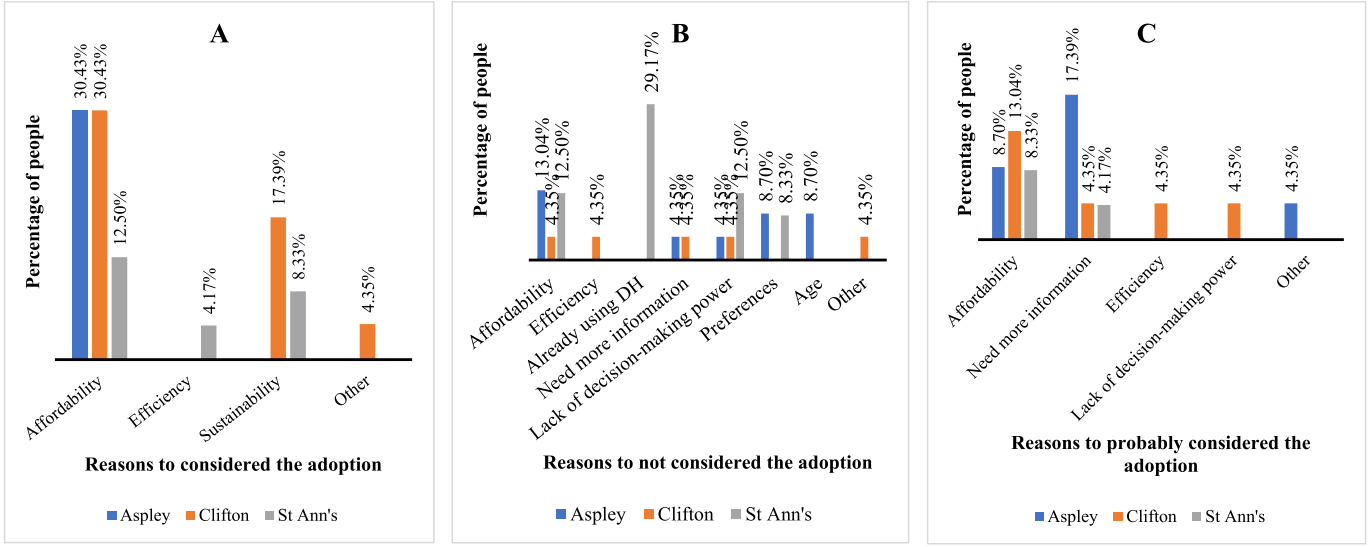

Fig. 6. Percentage of participants who would: a) consider switching to sustainable heating systems; b) not consider switching to sustainable heating systems; c) probably consider switching to sustainable heating systems.

The abundance, familiarity, and affordability of, and preference for gas-based heating contributes to its dominance, dependence and lock-in that resist change to new systems [13,21]. In fact, as seen in Fig. 6b and c, interviewees in Aspley and Clifton also showed some resistance to change their gas boiler since most of them would not consider or were sceptical about changing their heating system to a sustainable one. Similar findings were also reported by Sovacool et al. [4] in their study about European preferences for low-carbon heat that suggested that people are unlikely to change to a new system in the next few years due to low familiarity with the new systems and high satisfaction with their current heating systems. Participants' general concern was related to affordability of sustainable systems, but they expressed the need to have more information about the systems and its benefits to help them decide to adopt or not these systems in the future. Lillemo et al. [26] argue that consumers attitudes regarding the expected performance of new heating systems and its energy sources influence their heating investment behaviour.

However, participants shared that despite the environmental goal and benefits of these systems, running costs of the systems is the prime priority. As such, it must be cheaper to run than their current heating system as they are trying to reduce their financial challenges, especially now amid energy price rise and increase in the cost of living. In their study of the uptake of low carbon heating technologies in off-grid areas in the Southwest of England, Wrapson and Devine-Wright [11] reported many factors influencing the adoption of the technologies, and environmental-related reasons were also not the primary influence, but the avoidance of financial risks associated with 'peak oil'. Moreover, they reported that low carbon heating technologies were typically integrated into their existing conventional heating technologies rather than as a replacement in order to retain the valued services provided by conventional technologies. Again, this shows consumers resistance to decommission the use of their preferred heating system, even when other systems are installed in their properties. With current government's relaxation and delays in the phase out of gas boilers, it would be very challenging to make people change their attitude towards the adoption and use of sustainable heating systems.

In St Ann's most participants (62.5%) did not want to disconnect from DH to adopt another type of systems since, as argued by a 68 years' old male participant, they "*love DH for being brilliant, safe, good price and also good for the environment*". A BEIS' heat network consumer and operator survey conducted in 2022 also found a high level of consumers' satisfaction with DH (74%) due to the perceived fair and relatively low price, the amount of information provided on their bills, handling of complaints and outages [52]. While another market study of the domestic heat networks sector found that some people with negative experience of DH due to persistent issues with heating supply, billing and customer service shared they intention to avoid properties connected to DH in the future, and to advise their family and friends against buying properties along a heat network [40]. On the other hand, the fact that most people (around 79.17%) live in council-rented properties makes them unable to make decisions over the type of heating to be installed in the properties. This is also the case of some participants in the other study areas since, as previously shown in Table 1, around 43.48% of them in Aspley and 47.83% in Clifton live in council-rented properties.

This house tenure situation of most participants and that is also a commonplace across the UK, show that local councils and other social housing landlords have a much bigger role to play in the transition, acting not only as the usual planners of heat infrastructure but also as investors and adopters of sustainable technologies by investing in the purchase and installations of these technologies in council properties. Local authorities could also invest in disseminating information about technologies at local level to raise the low public awareness of the technologies, the country's plan to transition to sustainable heating systems and the need to adopt these technologies. For the latter, local authorities could also provide some grants to increase their adoption. However, considering the substantial financial challenges faced by the social housing sector, including higher spend on repairs and maintenance, high borrowing costs and inflation [53], it would be vital that the national government provides more financial, institutional, and technical support to local authorities and other social landlords. The recently announced up to £80 million of additional funding for home energy efficiency upgrades through the Social Housing Decarbonisation Fund (SHDF) is a good starting point, but its well below the £3.8bn fund originally promised for the SHDF and the 106bn of investment needed to decarbonise all existing social housing [54].

4.4. Awareness of the government heating transition plans

Following participants' answers on their likelihood of adopting sustainable heating systems, we asked them if they were aware of the government's plans to expand the domestic use of low carbon/sustainable heating system and if they think that the adoption of these systems should be optional or enforced. Most participants (71.43%) were not aware of the plans, while others were aware (25.71%) and probably aware (2.86%) of it. Clifton was the area where participants were less aware of the plans as only 3 (over 45 years old males) out of 23 interviewees replied positively. While participants from St Ann's were the most aware of the plans, compared to participants from Aspley and Clifton, and they shared some positive and negative viewpoints about the plans, as exemplified below:

> "I think it's good that the government is trying to do more to develop these technologies that are good for the environment, but I think they should do more to reduce the costs of installation and use of the technologies. Our current bills are painful, thus affordable costs will motivate people to adopt these technologies without being forced to (interviewee Nttg_St_020, April 2023)".

Despite the reduced level of awareness of these government transition plans, most participants (78.57%) believed in climate change, while the rest were unsure (10%), did not (5.71%) and sometimes (1.43%) believed in it. Most participants (40%) also believed in the negative impacts of their current heating systems on the climate. Of those participants, around 89.29% were using fossil fuel-based heating and 10.71% DH due to their scepticism regarding the sustainability of waste incineration for heat production. DH users also represented the 18.57% of participants who believed in the positive impact of their heating system on the environment. There were also a significant number of interviewees (28.57%) that did not have knowledge about the impact of their heating systems or that thought that their systems had no significant (11.43%) or no impacts (7.14%) on the climate. Most of these participants were under 40 and over 60 years old, and with professional qualifications. However, the latter were also part of the group of people who had more knowledge of the impacts of their heating system, while people under 40 and between 41 and 60 years old were as equally knowledgeable.

Nonetheless, most of those interviewees who did not have knowledge of the impacts or the extent of the impacts of their systems on the climate were also climate change believers. This shows participants' lack of correlation or knowledge of the level of contribution of their individual heating use to climate change compared to other pollution sources that they described as more impactful than domestic heating systems such as cars, large fossil fuel companies, and larger and more populated countries (e.g., China, India, Russia, and USA). A BEIS' survey of the UK public on the transition to a low-carbon heating future showed that there is a limited public awareness of the substantial contribution of heating to GHG emissions, with a third of gas-users perceiving their heating system as environmentally friendly [38]. The survey also showed a low level of public awareness of the country's plans to transition to sustainable heating systems in buildings, with older people, people with a degree, and those with higher incomes relatively more likely to be aware of the plans [38].

Nonetheless, as previously explained, most participants were not willing to change their current heating systems, which for most is also their preferred heating systems, arguing that they perform other environmentally conscious actions such as reduce their heating use, recycling or taking buses, rather than driving. According to Bandura [55]'s perceived self-efficacy theory, people are more likely and motivated to engage in a certain behaviour when they believe it is feasible, achievable and will lead to the expected outcome. Frederiks et al. [56] argue that people's pro-environmental behaviour is not reliably predicted by their knowledge of and concerns about what is the best or right thing to do for the environment since it is influenced by certain cognitive biases and 'irrational' tendencies that are predictable from the standpoint of psychology and behavioural economics. In fact, despite the current increase in gas price, most consumers continue to prefer gas-based heating systems. Moreover, because the electricity price has also increased, most consumers tend to use it as a justification to retain their gas-based heating, adding that despite the price increase, gas remains cheaper than electricity. Indeed, this was also one of the reasons that make some interviewees who have an electric fireplace installed in their properties (a feature of most council houses visited) not use it often.

As such, the majority of interviewees (71.43%) believed that the adoption of sustainable heating systems should be optional to allow people to evaluate the pros and cons of the systems, and to choose the one that is better for them, that they can afford. Moreover, considering that most of the participants have no decision-making power over their choice of heating systems, they believed that making it optional would allow them to lobby with their landlords for their preferred systems, rather than being forced to accept any system that landlords decide upon. While only 4.29% of interviewees believed that making the transition compulsory is ideal because it is better for the environment and because most people don't like changes and are not well informed, sometimes decisions must be made for them. They added that they would be happy to comply with the enforcement because they care for the environment. A 41 years' old male interviewee from Aspley[9] further added that "*these initiatives are welcoming and with the necessary* funding *and sensitization of households, it will be easier to convince them to transition to sustainable heating systems as they will be able to make an informed decision for their own advantage and everyone's advantage by sustaining the world*."

The remaining participants did not mind (8.57%) whether or not the transition is optional or compulsory since it is for a greater good, while others did not know (4.29%) or had an opinion on the matter (11.43%) since they didn't have much knowledge about it and because the ultimate decision will be made by their landlords, respectively. Notwithstanding all these diverse answers, the fact that there are still some government uncertainty and relaxation regarding their goals and commitments on the transition is likely to influence consumers rate and speed of adoption of and confidence in sustainable heating systems. Considering that the competitiveness of these systems for consumers will depends on their price and efficiency compared to the actual heating system in use [41], ultimately, most consumers are more likely to be laggard adopters since affordability of these systems is a major concern for them (see Fig. 6b and c). Therefore, in order to reverse this scenario and makers consumers early adopters and speed up the transition, it might be required that the government makes the price of these systems (including purchasing and running costs) more competitive than fossil fuel-based heating systems.

5. Conclusion

This paper assessed households' adoption of sustainable heating technologies in the United Kingdom. By taking the case of the Nottingham City, the paper aimed to deepen the understanding people's current engagement with their existing heating systems, and their awareness and perceptions of and willingness to adopt low-carbon heating is a crucial starting point [4], but very challenging. Households acceptance and adoption of sustainable heating technologies is vital for a successful transition to sustainable heating systems. However, transformative, and large-scale behavioural changes are needed in order to achieve that. Thus, a much deeper understanding of people's engagement with their current heating systems, their heating preferences, and awareness and perceptions of and willingness to adopt sustainable heating systems is a crucial but starting point. Our findings suggest that getting people to move away from fossil fuel-based heating is and will remain very challenging. Despite the price increase and reduction in consumption to reduce costs, fossil fuel-based heating systems continue to be the most preferred and familiar heating systems, perceived by most as more affordable, cost effective and efficient systems, including the capacity to retain the heat in a room for longer after turning it off. Because of that and the low level of awareness of sustainable heating systems, most people are not willing to consider adopting these systems.

Moreover, the high upfront cost of the systems and the potential financial unviability of the systems add an extra burden to their decision, especially now amid the current cost of living crisis that leads people to prioritise the reduction of their bills and financial challenges over environmental concerns. Government delays in the enforcement of development and uptake of these technologies as way to give the public more time to freely adopt the technologies will result in the late or no adoption of the technologies and the enduring lock-in of fossil fuel-based heating. While the availability of financial incentives such as grants and subsidies is useful to incentivise people to freely adopt the technologies, it may require more than this common type of incentive to incentivise people to change their current consumption behaviour and preferences for their valued service and have a positive attitude towards the adoption of these technologies.

There must be first the provision of non-financial incentives to increase people's awareness of sustainable heating technologies, and its financial and environmental benefits. These incentives will help reduce some of the sociotechnical and perceptual barriers to adoption of the technologies and motivate people to accept and engage in heat decarbonisation as a moral responsibility to the environment, and for current and the next generations. Ultimately, this will help to facilitate and speed up the transition to reach the goals set by the government. To this end, the government must have the necessary measures and enforcement in place and be more ambitious and committed to its transition and net zero goals to reduce gas-based heating's dominance, dependence and lock-in, as well as to reduce people's uncertainties and increase their trust on the effectiveness and benefits of the government transition plans.

The government must also actively involve local authorities and consumers in the process to help better safeguard consumers' interest (affordability, security of supply, and sustainability) – a model that has been successful in Denmark and Sweden, and will soon be replicated in the Netherlands [43]. This would increasingly help to encourage people to adopt the technologies, and discourage them from resorting or reverting to unsustainable heating alternatives such as fossil fuel-based heating or unusual heating sources for urban areas (e.g., solid fuels and gas canister-based heating) as verified with the two participants in Aspley and St Ann's.

5.1. Recommendations

Considering the high number of people with limited awareness of the substantial contribution of their fossil fuel-based heating to climate change, it will be essential to transform this scenario and make people completely aware of their (individual and collective) role as agents of change by transitioning to sustainable heating technologies. People must be aware and understand that their role in the transition go beyond being just passive heating users; they must shape and participate

[9] Interview Nttg_Aspley_001, May 2023.

actively in the transition process [7]. Local authorities could play a key at local level raising public awareness of their contribution and role, the technologies and the government heating transition plans and providing the necessary financial and non-financial incentives to households to motivate the early adoption of the technologies. However, it will be necessary to give local authorities more financial and institutional power in the transition, especially considering that they own a substantial number of properties but lack the necessary funding and support to improve the energy efficiency and the overall state of the properties.

Further, it is important to incentivise people to adopt the systems as early as possible to increase the likelihood of having a return of their investment while they are still living in their property. This will also increase the number of people with experience and user-perception of the technologies, who will then share it with their peers and influence their attitude towards the adoption of the technologies. Since older people perceive an investment in sustainable heating as bringing them less of a return, and people under 40 years old were less aware of the impacts or the extent of the impacts of their systems, and of sustainable heating systems, thus targeting young property owners to be early adopters will be crucial. However, declining levels of home ownership clearly restrict the usefulness of this measure and point to the importance of considering the private rented sector's transition as well.

Considering that currently people have mixed experiences with sustainable heating systems, despite being mostly satisfied, it is important to address their concerns or at least the most relevant ones such as running costs and efficiency to ensure that people have the necessary and expected thermal comfort. A transparent and affordable price and more efficient sustainable heating technologies compared to their current systems will make the technologies more competitive. Therefore, it is important to have effective and just business models and pricing mechanism in place, along with efficient and sufficient technical staff. The latter will require providing more technical training and job opportunities to people. The fact that people with professional qualification are the ones most and least aware of and willing to adopt sustainable heating systems can be advantageous to this end and be early adopters of the systems. It is also important to invest more in technological innovation to allow researchers to have the necessary means to continue to make advances in improving the efficiency of the systems.

CRediT authorship contribution statement

Daniela Salite: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ying Miao:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Ed Turner:** Writing – review & editing, Visualization, Supervision, Resources, Project administration. **Yuan Feng:** Visualization, Software, Methodology, Investigation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

This research was conducted as part of the project: VTTESS-Variable-Temperature Thermochemical Energy Storage System and Heat Networks for Decarbonising the Buildings Sector. This project is generously supported by the Engineering and Physical Sciences Research Council (EPSRC), UK under Grant No. EP/V041452/1, held at University of Nottingham (Prof Jo Darkwa) and Aston University. The authors wish to thank all the people that have supported this research.

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