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Understanding preferences for low-carbon technologies, retrofit and ownership models for domestic heating in the UK

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ABSTRACT

Despite advancements in renewable energy technology adoption, the uptake of low-carbon heating technologies in the UK and many other countries remains insufficient to align with governmental objectives and targets. This has been attributed mainly to high capital costs, limited consumer awareness, and unclear economic and environmental benefits. This study aims to understand these challenges and analyse ways to overcome them by exploring consumer willingness to support the transition to low-carbon heating through adoption of low-carbon heating appliances, property retrofit and novel ownership and control models, using data from a two-wave survey of over 1000 UK households conducted in 2023–2024. The first wave assesses current household contexts, which inform three stated-preference scenarios in the second wave: (1) choosing between gas boilers, hydrogen-ready boilers, and air-source electric heat pumps, with varying costs, emissions, and support schemes; (2) deciding on retrofit levels (none, minor, major) characterised by costs, savings, and support; and (3) selecting between ownership and operation models (full ownership, shared ownership, service-based heating), each with different costs, contract lengths, and flexibility features. By using discrete choice modelling, the analysis provides insights into how different consumer segments, defined by sociodemographic and attitudinal factors, respond to attributes such as capital and operational costs, as well as the impact of support schemes. The study estimates willingness to pay for reduced nuisance or emissions, and the compensations required for participation in flexible pricing or demand-side response, offering guidance for policies that encourage low-carbon heating adoption across diverse user groups.

1. Introduction

Decarbonisation of the energy sector is essential to achieve the desired net-zero emission targets set by the UK and other nations. While decent progress has been made on the decarbonisation of electricity supply, heating, which constitutes a substantial proportion of the energy consumption and GHG emissions in many countries, is lagging behind. The heating and cooling sectors alone contribute to almost half of the total energy consumption in Europe [1]. Globally, similar patterns are observed [2] Much of domestic space and water heating is still derived from fossil-fuel combustion in gas boilers and oil burners, which has detrimental environmental impacts.

The adoption of low-carbon heating technologies has now emerged as a matter of paramount importance. Despite recent advancements, the uptake of low-carbon heating technologies is not on pace to meet policy targets [3]. This is due to various reasons, mainly including the

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substantial capital cost of new low-carbon heating technologies, the lack of consumer awareness regarding their reliability [4], and the absence of detailed information regarding the potential for substantial economic and environmental benefits for the consumers themselves [5]. Even if the economics of low-carbon heating technologies are favourable over their lifetime, the initial investment cost represents a significant hurdle for many households and potential future energy cost savings are often heavily discounted in the decision-making process [6].

Electric vapour-compression heat pumps are a well-established technology that uses electricity to provide space heating and domestic hot water, offering a significantly better thermodynamic performance and a longer lifespan compared to boiler systems [7,8]. Although they have experienced a remarkable market growth, achieving growth rates exceeding 10% per year in Europe from 2014 to 2022, the deployment of clean heating technologies needs to accelerate further. However, the heat pump market experienced its first decline in a decade in 2023, with the downturn deepening in 2024 [9]. In their latest analysis, the European Heat Pump Association (EHPA) attributed this to inadequate and delayed subsidies, high electricity prices compared to gas, regulatory uncertainty and a slow processing of new projects and retrofits in building applications in various European countries [10]. In the UK, the shift to electric heating is a large part of the government's decarbonisation strategy [11]. However, the economics of a shift to heat pumps depend strongly on natural gas prices [12].

Another notable alternative for heat decarbonisation, widely discussed in both academic literature and industry, is replacing natural gas or oil in boilers with hydrogen (Element [13]). This approach would benefit from repurposing existing natural gas infrastructure, and could be especially advantageous in countries with extensive networks and use, such as the UK. From a household perspective, hydrogen boilers promise significantly lower upfront investment costs compared to heat pumps. However, the transition is not straightforward due to the significant costs of system-level equipment upgrades (Chelsea [14]), and potential resistance to change arising from concerns over cost, safety, and resistance due to the complexity of adopting new technologies. For example, the UK's 'Hydrogen Village' trial of 2000 households in Whitby, Ellesmere Port was cancelled in 2023 due to opposition from the local community [15]. Furthermore, depending on the cost of hydrogen, operating costs could be substantially higher compared to heat pumps due to the lower efficiency.

Unlike the decarbonisation of the electricity supply sector, which operates largely in the background of daily life, decarbonising heating engages people on a far more personal level. Ultimately, as long as electricity is available in a reliable and low-cost fashion, many households, especially facing high costs of living, may not be too concerned with how this electricity was generated. Heating, however, demands more direct involvement: it requires homeowners to make decisions about technological changes within their own homes. Such decisions will inevitably be shaped not only by the economics, but also personal values, comfort, environmental concerns, or trust in innovative technologies among other things. Moreover, decisions concerning heating involve not only the heating technology, but also investments in energy efficiency of the property (retrofit) as well as a decision on how the heating system is owned and operated. Understanding the attitudes and preferences of households regarding different heating technologies in conjunction with retrofit options as well as ownership and operation models is key in designing effective heat decarbonisation policy.

1.1. Research gap and novelty

Several studies have recently looked at the role and comparison of low-carbon heating technologies from both a technological and an energy system perspective [16,17]. A crucial aspect that warrants further research concerns the willingness of consumers to financially support this transition, including understanding the roles of associated retrofit or presence of demand-side response (DSR), and how to best support consumers in making decisions aligned with national decarbonisation goals. Thus, the present study considers domestic heating decarbonisation as not only a shift towards low-carbon heating technology (appliance) choice, but also upgrades to property energy characteristics as well as consideration of emerging business models and participation in services that may make heating transition more affordable on the one hand, but also beneficial to energy system as a whole on the other ().

Addressing the challenges in adopting low-carbon heating requires advancements in education, pilot programs to build trust and demonstrate the feasibility of various solutions, and financial incentives [18]. The most crucial step to implementing these measures effectively is the development of more realistic representations of decision-making behaviours. Without this, available tools may produce unrealistic predictions that fail to account for factors such as attitudes, trust, and non-economic considerations.

To address these shortcomings, this study offers findings from the analysis of a two-wave online survey of 1027 households in the UK conducted between October 2023 and April 2024. Wave 1 of the survey seeks to understand the current context of households which serves as inputs to creating three tailored stated-preference (SP) scenarios in Wave 2. In the first SP scenario, respondents are asked to choose their preferred heating option from three choices: gas boiler, hydrogen-ready boiler, and air-source heat pump, characterised by different capital and operation costs, support scheme, maintenance, and CO_2 emissions. In the second SP scenario, the choice is made between retrofit scenarios (none, minor, major), characterised by various equipment cost, retrofit costs, expected savings, nuisance and support schemes. In the third SP scenario, the respondents are asked to select between different ownership and operation models, i.e., full ownership, shared ownership and service-based heating, characterised by upfront costs, annual cost of operation, contract length, energy pricing variability and control and service flexibility (for DSR).

By examining this dataset using a discrete choice modelling (DCM) methodology, the analysis seeks to accomplish the following research objectives: (a) firstly, it identifies and quantifies the magnitude of key drivers influencing the selection of specific heating technologies, retrofit options, and ownership schemes; (b) secondly, it provides insights into how these drivers vary among different customer segments, defined by sociodemographic factors, property types, and attitudes; and (c) thirdly, it provides estimates of the consumers' willingness to pay and accept various attributes associated with heating technologies, retrofit options, and ownership models, including reductions in nuisance and carbon emissions and calculates the compensation required for participation in flexible pricing and DSR. Consequently, the study provides a uniquely comprehensive overview of how different policy levers can facilitate the transition towards low-carbon residential heating among different user groups.

The analysis presented here is a valuable resource for policymakers, energy planners, and modellers. Not only does it provide directly useful knowledge, such as willingness-to-pay estimates, but it also helps develop improved agent-based models of low-carbon heating adoption, providing a more realistic representation of decision-making in whole-energy systems. By integrating survey data on consumer willingness to pay and diverse customer segment decision processes into UK whole-energy system optimisation tools, we can in future move beyond the current central planner perspective and the idealised rational decision-making models found in most studies [19]. This approach will ultimately provide a means of more accurate modelling of heterogeneous agents' preferences and, thus, better assessment of expected policy impacts across the entire energy sector.

2. Literature review

Homeowners' attitudes towards different heating technologies and factors influencing the adoption of various technologies have been extensively studied in the academic literature. Already in 2008,

Mahapatra and Gustavsson [20] published results from two surveys of 1500 homeowners on heating technologies conducted in Sweden in 2004 and 2007. The results showed that less than 20% of respondents were planning on changing their heating system, and an investment subsidy for district heating, heat pumps and woodfired boilers available from the government was only of little importance for about half of the respondents, despite people with such innovative heating systems being more satisfied overall. The survey also showed that investment and annual costs as well as reliability were the most important factors determining the choice of new heating system, and that communication with local vendors/installers was the most important source of information, outperforming e.g., media campaigns. Similarly, Michelsen and Madlener [21] analysed homeowners' preferences regarding innovative heating technologies based on a 2009/2010 survey of 5000 German households (2985 responses), also focussing on investment cost subsidy mechanisms. As in the Swedish case, the subsidy was found to have only a small impact on the decision to adopt heat pumps and solar-thermal assisted boilers, while a combination of homeowners' attitudes as well as building and sociodemographic characteristics were found to be more significant. It is important to note though that at the time the surveys were conducted, the penetration of innovative heating technologies was still relatively low, and only early adopters were switching to these technologies.

Ruokamo [22] performed a choice experiment by surveying 2000 Finnish new detached homeowners (432 responses) in 2014, focussing on attitudes towards hybrid heating systems. The author calculated willingness-to-pay estimates and showed that ground-source heat pumps and district heating were the most popular main heating systems. Gas boilers were not available as an option to choose from. The results showed that respondents were sensitive to investment and operating costs, but comfort of use was also a highly significant factor, and environmental performance of different heating systems also played a role in the decision-making process. A preference for more convenient district heating systems is also reported by Yoon et al. [23], who surveyed 400 individual-heating and 400 district-heating users in the Republic of Korea in 2014. In that survey, 64% of respondents preferred district heating systems. It was estimated that users are willing to pay 4 to 12% higher rates for district heating.

Franceschinis et al. [24] specifically evaluated the willingness to pay for lower-carbon heating solutions in the Veneto region in Italy in 2016. The authors stressed regional and socio-demographic differences in willingness to pay, showing that respondents living in in mountainous regions tend to show a higher willingness to pay for emission reductions. Similarly, people in small towns and people with higher income tend to have a higher willingness to pay. Overall, the willingness to pay of the respondents was between −2 and 10 EUR/(kgCO_2/year). On a larger scale, Karytsas et al. [25] more recently compared the willingness to pay for a heating and cooling system consisting of ground-source heat pump, solar thermal collectors and thermal energy storage in Greece, Portugal, and Spain. Even though the perceived benefits and willingness to adopt were similar across the three countries, respondents from Spain showed a higher willingness to pay. Overall, people with a high level of education and higher-than-average income, living outside urban areas, using conventional heating and spending more-than-average on energy show a higher willingness to pay.

In 2021, Sovacool et al. [26] surveyed over 10,000 households in Germany, Italy, Spain, Sweden and the UK to determine regional differences in attitudes towards heating systems. The results showed that about a third of respondents were willing to pay more than 20 EUR/month extra for low-carbon heating, another third 1 to 20 EUR/month, and the final third was unwilling to pay extra for low-carbon heating. Households in Sweden were most likely to be willing to pay more than 20 EUR/month (47%), while households in the UK were the least likely (18%). Only 18 to 26% of respondents were supportive of innovative business models for heating, such as leasing of assets or heat-as-a-service.

Focussing on heat pumps, Hadush Meles et al. [27] in 2018 combined a discrete choice experiment with psychological construct statements to estimate the willingness to pay for different attributes of heat pumps of Irish households. Respondents were clustered in 4 classes based on their responses to the psychological construct statements, with 23% being pro heat pumps, 17% against, 22% neutral and 37% moderate. Respondents with a higher level of education and higher income were more likely to be supportive of heat pumps. The upfront investment costs were found to have the largest relative importance on the choice of heating technology (42%), followed by energy bill savings (23%), while installation efforts (9%), environmental sustainability (5%), and increase in comfort (3%) only played minor roles. The mean marginal willingness to pay for a 50% and 75% energy bill reduction was 10,500 and 12,200 EUR, respectively, while the marginal values of moderate and high environmental sustainability were 500 and 2600 EUR, respectively. On the other hand, the marginal willingness to pay for a high installation effort was −5300 EUR, indicating that respondents are reluctant to accept high installation efforts. Interestingly, the differences in marginal willingness to pay between the different classes were low, with e.g., respondents that tend to be against heat pumps showing approximately the same willingness to pay for high environmental sustainability as respondents in favour of heat pumps.

Strazzera et al. [28] performed choice experiments in 2021 to compare willingness to pay for different heat pump systems in Ireland and Italy. They defined three classes: early adopters, laggards, and late adopters. In Ireland, only users in the first class were willing to pay for new heating systems. They were willing to pay about 10,000 EUR for each of the technology options and valued an additional 10% in energy bill savings at 390 EUR, and a 10% emission reduction at 350 EUR. Italians in the first class on the other hand were willing to pay 13,800 EUR for heat pumps with gas backup, 20,500 EUR for standalone heat pump systems, and 27,600 EUR for heat pumps with photovoltaics (PVs). A 10% reduction in energy bills and emissions was valued at 2100 EUR and 690 EUR, respectively. Late adopters in Ireland attached a large marginal value to emission reductions (1900 EUR for a 10% reduction), while late adopters in Italy attached no value to emission reductions at all.

Rekker et al. [29] performed a comprehensive willingness-to-pay discrete choice experiment in the Netherlands in 2022, considering natural gas, electric and hydrogen heating systems at different emission intensity levels, while also distinguishing between individual and district heating. The authors found a similar willingness to pay of 21 to 22 EUR/month for electricity and hydrogen heating systems. Unlike Ruokamo [22] and Yoon et al. [23], Rekker et al. [29] found a negative willingness to pay of −12 EUR/month for district heating, indicating that respondents preferred individual heating solutions. Correspondingly, having a choice of energy provider was valued at 11 EUR/month. The authors calculated two willingness-to-pay values for reducing CO_2 emissions: if upfront installation costs increase, respondents are willing to pay 51 EUR/tCO_2 avoided, while if monthly bills increase, the willing-to-pay increases to 114 EUR/tCO_2. This indicates that respondents were more sensitive to increases in upfront investment costs. The authors defined 7 latent classes based on the responses, with price-sensitive (25%) and unremarkable (21%) accounting for the largest shares of respondents.

A different perspective to the topic was provided by Bai et al. [30] who surveyed about 400 households in rural China in 2021 and 2022. In their sample, 42% of respondents were illiterate and less than 9% had received any high school education. Results showed that the probability of adopting electric heating over coal or biomass increased significantly with education levels. The average willingness to pay for clean heating was about 150 USD/year. The authors highlighted that affordability of fuel played a critical role in heating technology decisions.

Wall and Laing [31] surveyed 61 households in Scotland that have already switched to heat pumps, making them early adopters in the UK. The survey revealed that the most important factors were carbon

savings, thermal comfort, and a reputable installation company, while government policy and disruptions during the installation were mostly viewed as unimportant. Overall, 80% of respondents were very satisfied with their heat pump, while only 1 was slightly dissatisfied and another 1 was very dissatisfied.

An evidence review of public awareness and attitudes towards low-carbon heating technologies identified that the expected cost and uncertainty about performance are two main factors that put people off low-carbon heating systems [32]. In addition, concern about climate change and general awareness of low-carbon systems were shown not to be sufficient to increase the uptake of low-carbon heating systems, and financial support alone is also not enough to persuade consumers. Similarly, a trial over the winter of 2018–19 with heat pumps and hybrid heating systems also observed that when offered a free heat pump, participants were still put off by uncertainty around the rising running costs and uncertain performance [33]. Due to such concerns about cost and performance of low-carbon heating systems, other support strategies and services have been promoted recently, including retrofitting, district heating and heating-as-a-service (HaaS) or participation in grid services, such as DSR aimed at generating additional customer revenues.

Bayer & Pruckner (2024) simulated the environmental impact of switching from gas boilers to heat pumps and the accompanying building retrofitting in a digital twin of a German city. The results showed that insulation retrofits would significantly increase CO_2 emission reductions from 19 to 30% to 27–37% across different years. Liu et al. [34] conducted a stated choice experiment with 380 social housing tenants in the Netherlands in 2021 to determine the influential factors in participating retrofits and participants' preferences. Their findings indicate that total housing cost, living comfort and nuisance are three key factors. Furthermore, tenants prefer retrofits that can also improve their facilities and neighbourhoods, such as the renovation of bathrooms and water drainage. Fleck et al. [35] argued that retrofitting and emergent services such as HaaS could be necessary to guarantee thermal comfort and provide financial solutions for low-carbon heating. However, the development of HaaS is still limited and the barriers to uptake include: (a) lack of awareness about HaaS; (b) low digital literacy and digital exclusion; (c) length of the contract with energy providers and the switching regulation between suppliers; (d) disruption and cost; (e) no clear policy on social equity; and (f) lack of support from policy, tariff rules, licensing and heat decarbonisation strategies [35,36].

DSR traditionally employs the flexibility of electrical assets or generation to provide balancing services. Similarly, the operation of electric heating technologies with thermal energy storage, as well as the thermal mass of buildings can be used as methods to respond to grid signals, potentially reducing costs and greenhouse gas emissions. The Balanced Energy Network (BEN) at London South Bank University campus is the UK's first Fifth Generation District Heating and Cooling (5GDHC) system at scale [37]. This system retrofitted two existing gas-heated buildings, linking them with smart thermal storage tanks and an active DSR control system to minimise cost and carbon emissions. The estimation at the design stage indicated that demand response revenue could equal about 10% of utility costs for each building. After the first year of operation, BEN maintained the original thermal comfort and reduced overall building carbon emissions by 13% and gas use by 40%.

Ouf et al. [38] analysed the results of a survey with 472 responses in Quebec, Canada in 2022 and 2023, to understand occupants' perceptions of DSR and their participation in peak demand events. Residential heating and cooling in Quebec are mostly electric and reducing the space heating setpoints is the best way to save money through DSR [39]. In the survey [38], about 75% of participants indicated they decreased or would decrease thermal setpoints during peak demand periods. This survey finding aligns with the data from Hydro Quebec that 77–78% of residential customers lowered their heating setpoints by over 2 °C during peak events in the winters of 2019–2021 [39]. However, the survey in Quebec also found that about 25% of participants increased or would increase heating setpoints during peak demand events and over 75% of participants indicated that they override DLC events more than 10 times per year. This unexpected reaction underscores the urgent necessity to enhance occupants' education and awareness of demand response (DR) in general, as well as to clarify their expected roles during peak demand events. The survey results also indicated that education and income levels significantly influence participation in DSR programmes.

Motivated by the aforementioned and previous studies [40], the present analysis recognises that the transition towards low-carbon heating system consists, and thus requires comprehension, of three decision elements:

1. Choice of heating technology,
2. Consideration of the property's energy efficiency and potential retrofit measures,
3. Choice of heating system ownership model and control.

This decomposition provides a means of distinguishing effective drivers, barriers and thus policy levers for different decarbonisation strategies, ranging from subsidies for low-carbon heating appliances, to improved energy efficiency through measures such as insulation, and to the implementation of variable pricing and DSR services. This presents a novel approach compared to existing studies, which tend to focus on a subset of these decision elements (per Table 1 above). In the present study, we investigate these three decision steps in three distinct choice experiments. The research methods are described in Section 3, the results are presented in Section 4, followed by a discussion and conclusion in Section 5.

3. Methods

Fig. 1 illustrates the methodological steps of this study. The datasets and models are explained in detail in the following sections.

3.1. Data

The survey analysed in the present work consists of two successive waves (Wave 1 and Wave 2) administered to the same respondents across the UK between October 2023 and April 2024. The two-wave design was motivated by the intention to tailor the stated preference design (in Wave 2) using information about the respondents obtained in Wave 1.

The data were collected using an online panel of respondents made available by market research company Norstat [42]. Upon invitation and consent to participate, respondents were sent the questionnaires implemented on Qualtrics via Nortstat's distribution system and rewarded accordingly by Norstat upon completion.

The survey targeted 1100 responses and achieved 1027 in Wave 1, with quotas applied to ensure representation of respondents with different combinations of the following attributes (Table 2):

- property ownership (since owners are primarily responsible for heating system acquisition and maintenance);
- occupancy status i.e., residing in the property (resident) or renting out (landlord), since personal exposure to the heating system may affect decisions, especially considering that landlords would typically pay the upfront investment costs but not benefit from monthly bill savings;
- type of heating system, with particular focus on gas boilers due to their current high prevalence in the UK market;
- timing of the most recent heating technology replacement, since users who recently underwent that process may be better informed but less inclined to undergo another replacement in the near term.

By design and intended policy focus, the sample composition is biased towards overrepresentation of gas boiler-based heating owners. In the context of the UK, this is, however, key segment of population as

Table 1
Summary of the discussed studies.

Study	Sample	Method	Technology choice (WTP)	Retrofit	Ownership and operation	DSR	WTP
Mahapatra and Gustavsson [20]	$N = 1500$ (Sweden)	Survey, descriptive analysis	YES	NO	NO	NO	NO
Michelsen and Madlener [21]	$N = 5000$ (Germany)	Survey, regression	YES	NO	NO	NO	NO
Ruokamo [22]	$N = 2000$ (Finalnd)	Survey, discrete choice modelling	YES	NO	NO	NO	YES
Yoon et al. [23]	$N = 400$ (South Korea)	Survey, discrete choice model	YES	NO	NO	NO	YES
Franceschinis et al. [24]	$N = 223$ (Italy)	Survey, discrete choice analysis	YES	NO	NO	NO	YES
Karytsas et al. [25]	$N = 201$ (Greece)	Survey, regression	YES	NO	NO	NO	NO
Sovacool et al. [26]	$N = 2009$ (Germany), Italy (2039), Spain (2038), Sweden (2023), UK (2000)	Survey, descriptive analysis	YES	YES	YES	NO	YES
Meles et al. [27]	$N = 1208$ (Ireland)	Survey, latent class analysis, discrete choice analysis	YES	NO	NO	NO	YES
Strazzera et al. [28]	$N = 1299$ (Ireland); 1417 (Italy)	Survey, latent class analysis, discrete choice analysis	YES	NO	NO	NO	YES
Rekker et al. [29]	$N = 1794$ (Netherlands)	Survey, latent class analysis, discrete choice analysis	YES	NO	YES	NO	YES
Bai et al. [30]	$N = 400$ (China)	Survey, regression, discrete choice analysis, structural equation model	YES	NO	NO	NO	YES
Wall and Laing [31]	$N = 61$ (Scotland, UK)	Survey, descriptive analysis	YES	NO	NO	NO	NO
Energy Systems Catapults [33]	UK = 5	Living lab trial	YES	YES	YES	NO	NO
Bayer & Pruckner [41]	Germany	Simulation	YES	YES	NO	NO	NO
Liu et al. [34]	$N = 380$ (Netherlands)	Survey, discrete choice analysis	NO	YES	NO	NO	YES
Fleck et al. [35]	Scotland	Feasibility study	NO	NO	YES	NO	NO
Gillich et al. [37]	UK	Feasibility study	NO	YES	YES	YES	NO
Ouf et al. [38]	$n = 472$ (Quebec, Canada)	Survey, descriptive analysis	NO0	NO	YES	YES	NO

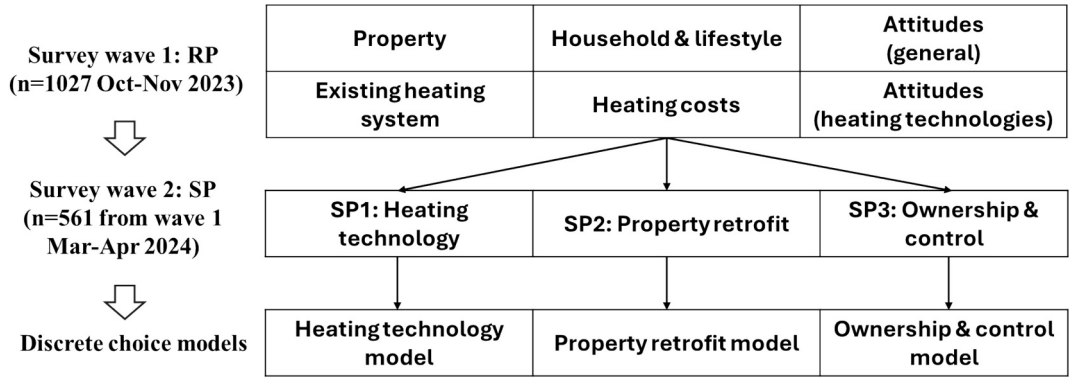


Fig. 1. Methodological steps.

domestic heating with natural gas accounts for ca. 73% [43] of the entire population. Consequently, the current findings needs to be translated with caution into market segments or geographies where such prevalence is lower.

Moreover, the survey excluded respondents who (or whose families) in the preceding five years worked in any sector that could possibly bias their responses: advertising, marketing/market research, energy, utilities, plumbing/heating, public relations, local government, following the approach by Williams et al. [44]. This criterion was applied to ensure a participant profile representative of the general public, minimising bias due to views or inside knowledge that involvement in such sectors could entail. The exclusion of energy related professions was driven by the intention to gain understanding into trade-offs that are associated with typical (non-expert) decision-makers, rather than be driven by knowledge not generally available to members of the public. In other words, we decided to sacrifice representativeness (which would not be achievable given the focus on gas boiler owners, as per below) for the sake of more consistent insights into decision mechanisms of typical decision-makers [45].

As for the survey content, the main motivation for Wave 1 was to understand the present situation of the households. Thus, it contained questions divided into seven blocks covering:

- the property, including floor area, age, insulation, appliances;
- the existing heating system, including the source of heat, temperature settings, perception of the heating performance, energy consumption;
- the current heating costs;
- the household attributes, e.g., size, composition, income, and lifestyle, e.g., work from home, typical activities at selected times of day;
- general attitudes towards environmental issues and trust in information sources;
- attitudes towards various heating technologies as well as possible assurances and incentives;
- other comments they may have.

The content of the Wave 1 survey was informed extensively by past research and survey efforts such as BEIS (2020), Fylan et al. [46] and

Table 2
Segmentation approach for Wave 1 of the survey. Targeted and actual sample sizes are segmented based on property ownership, occupancy, heating system type, and recency of heating replacement.

Segment	Targeted responses		Actual responses		Owns property they live in	Has another property	Gas boiler heating	Recently (< 1 year) replaced heating	Asked about the rented property (as the landlord)
	Count	%	Count	%					
A	100	*9%*	17	*1.7%*	YES	YES	YES	YES	NO
B1	150	*14%*	67	*6.5%*	YES	YES	YES	NO	NO
B2	150	*14%*	62	*6.0%*	YES	YES	YES	NO	YES
C	50	*5%*	3	*0.3%*	YES	YES	NO	YES	NO
D	50	*5%*	58	*5.6%*	YES	YES	NO	NO	NO
E	100	*9%*	46	*4.5%*	YES	NO	YES	YES	n/a
F	300	*27%*	596	*58.0%*	YES	NO	YES	NO	n/a
G	50	*5%*	6	*0.6%*	YES	NO	NO	YES	n/a
H	50	*5%*	52	*5.1%*	YES	NO	NO	NO	n/a
					NO	YES	YES	YES	NO
					NO	YES	YES	NO	NO
					NO	YES	NO	YES	NO
					NO	YES	NO	NO	NO
I	100	*9%*	120	*11.7%*	NO	NO	YES	YES	n/a
					NO	NO	YES	NO	n/a
					NO	NO	NO	YES	n/a
					NO	NO	NO	NO	n/a
Total:	1100	*100%*	1027	*100%*					

ARUP [47]. The survey design was peer-reviewed by practitioners and researchers from the energy industry to ensure alignment with industry practice, taxonomy and categorisation, maximising its relevance and impact.

Whilst Wave 1 of the survey was devised to understand the 'status quo' of the respondents' heating context, the primary objective of Wave 2 was to elicit their preferences in relation to heating technologies, retrofit options, as well as ownership and control, by means of three stated preference (SP) experiments. Table 3 summarises these experiments, outlining the available options and attributes characterising each (see Sections 3.1.1–3.1.3 for more details).

Importantly, to present realistic stated choice experiments, scenarios were tailored according to the property type (flat and apartment vs. house and other), property size, and year in which the property was built (Table 4). Thus, attributes of the presented alternatives, e.g., equipment or retrofit costs, were tailored in accordance with the respondents' circumstances determined based on the responses from Wave 1, which is a common practice and the motivation behind two-wave surveys in other contexts, e.g., travel behaviour modelling [48].

These three SP experiments (SP1, SP2 and SP3) followed a fractional factorial design with 4 blocks for each segment. Overall, 6 scenarios were presented to each respondent per SP experiment. The optimal design was obtained using the Ngene software tool [49]. Tables 5–7 below outline how attribute levels were derived for each of the attribute and segment combinations.

Table 3
Stated choice (preference) experiments – summary.

Experiment	SP1	SP2	SP3
Focus:	**Heating technology**	**Property retrofit**	**Ownership and control**
Choices:			
Option 1	Natural gas boiler	No retrofit	Full ownership
Option 2	Hydrogen-ready boiler[1]	Minor retrofit	Shared ownership
Option 3	Air-source heat pump[1]	Major retrofit	Service-based
Attributes:	Fixed cost	Equipment cost	Upfront cost
	Operation cost	Retrofit cost	Operation cost
	Support scheme	Nuisance duration	Contract length
	Maintenance visits	Cost savings	Energy pricing
	CO_2 emissions	Support scheme	Control and flexibility

[1]The order between hydrogen-ready boiler and air-source heat pump options was random as there was no natural way of ordering these alternatives and to remove order bias.

3.1.1. SP1: Heating technology choice

The technology choice SP had three alternatives, described as follows:

- *Natural gas boiler:* The conventional gas boiler combusts natural gas to heat water, which is then circulated through radiators or underfloor heating systems to warm indoor spaces. Combustion of natural gas produces emissions, such as CO_2, at the point of use. This technology has been around for decades and is currently by far the most common heating system in the UK.
- *Hydrogen-ready boiler:* A hydrogen-ready boiler is designed to operate initially on natural gas and to be converted to use up to 100% hydrogen if hydrogen supply and suitable network infrastructure become available. Conversion would involve an in-situ process using a manufacturer-supplied kit and would be carried out by an appropriately trained gas engineer [60]. Following conversion, the boiler would produce no CO_2 at the point of use, but the overall carbon emissions depend on how hydrogen is produced and supplied. The existing gas network could potentially be adapted to distribute hydrogen, subject to the required infrastructure upgrades and repurposed pipelines. Hydrogen-ready boilers are included as a prospective low-carbon heating option that could allow households to retain a familiar boiler-based system while providing a pathway to transition to hydrogen in the future. This also provides insights into how emergence of alternative boiler-based heating technologies can interfere with the long-term electrification objectives, currently championed as the primary pathway towards decarbonisation [61].
- *Air-source heat pump:* An air source heat pump uses electricity to extract heat from the ambient air (even when it is cold, e.g., during winter) and increases its temperature to heat water, which is then circulated through radiators or underfloor heating systems to heat homes. Heat pumps do not produce emissions at the point of use but consume electricity that may be associated with emissions during generation. The technology has been available for domestic heating for decades [62].

The order in which the latter two alternatives were provided to the respondents was randomised across them to minimise the risk of order bias.

Table 4
Segmentation approach for the stated preference.

Segment number	1	2	3	4	5	6	7	8
Property type	Flat (incl. apartment)				Not flat			
Property size	Up to 70 m^2	Up to 70 m^2	Above 70 m^2	Above 70 m^2	Up to 100 m^2	Up to 100 m^2	Above 100 m^2	Above 100 m^2
Property built year	Before 1965	1965 or after	Before 1965	1965 or after	Before 1965	1965 or after	Before 1965	1965 or after

Table 5
Summary of attributes and levels in the SP design on heating technology choice.

Attribute name (unit)	Explanation provided to the respondents	Number of levels	Source of values
Fixed cost (£)	One-off purchase and installation cost of the heating appliance.	3	([50]; [51])
Cost of operation (£ per month)	Typical monthly cost of heating, including maintenance.	3	([52]; [17])
Support scheme	Availability of preferential loans to help cover the cost of purchasing the heating appliance.	3	None, interest-free and 4% loan assumed
Maintenance visits (per year)	Number of annual visits by a skilled technician for maintenance (cost is included in the operation cost).	2	1 or 2 visits per year assumed
CO2 emissions (kg per year and equivalent number of London-Glasgow flights)	Annual CO_2 emissions produced when using the heating technology, either directly (combustion) or indirectly (generation of required electricity).	3	[53]

3.1.2. SP2: Property retrofit choice

The property retrofit choice experiment presented respondents with three alternatives:

- *No retrofit:* Only the heating appliance is replaced.
- *Minor retrofit:* In addition to replacing the heating appliance, minor upgrades such as draught proofing, reducing infiltration, and insulating the hot water tank insulation are undertaken to reduce energy consumption.
- *Major retrofit:* In addition to replacing the heating appliance and minor retrofits, wall, floor, and loft insulation as well as upgraded window insulation (double or triple glazing) are implemented. This is more expensive and causes more nuisance but leads to more substantial energy savings.

3.1.3. SP3: Ownership and control choice

The choice set of the ownership and control SP comprised the following three alternatives:

- *Full ownership:* The end-user fully owns the heating system and is responsible for the maintenance of the equipment and its operation.
- *Shared ownership:* The end-user shares ownership of a larger heating system with their neighbours/community. This reduces the overall cost of equipment and operation, but potentially reduces control over how the system is operated and maintained.
- *Service-based:* The end-user does not need to purchase the equipment, as this is done by the service provider. Consequently, there is no upfront cost. In exchange, they may need to pay more on a monthly basis for the duration of the contract that is signed with the service provider.

Table 6
Summary of attributes and levels in the SP design on property retrofit.

Attribute name (unit)	Explanation provided to the respondents	Number of levels	Source
Equipment cost (£)	One-off cost of the heating appliance, including installation; remains fixed for each scenario.	3	Values derived from average values of fixed cost of gas boiler, hydrogen-ready boiler and air-source heat pump in SP1.
Retrofit cost (£)	One-off cost of the retrofit option, including parts and labour.	3	[54]
Nuisance duration (days)	Number of days of expected installation and retrofit works required. This may involve contractors working in the property.	2	1 or 2 days (no and minor), 7 or 14 days (major) assumed.
Savings and payback period (£ per month)	Expected energy bill savings as a result of the retrofit.	3	Derived from minimum and maximum running costs and saving percentages associated with the retrofit options. The payback period was the period over which the resulting savings would accumulate to the value of the retrofit costs.
Support scheme	Availability of preferential loans (interest-free loan or 4% loan) to help cover the cost of the heating technology replacement and retrofit works.	3	None, interest-free and 4% loan assumed.

3.2. Sample composition

Table 8 presents the summary of the characteristics of the sample collected in the survey. The sample, as expected, is skewed towards households with gas boilers. This reflects the focus of the survey on this group whose views are of primary interest in the context of heating decarbonisation. However, the electric boiler ownership rate of survey respondents is also comparatively high [63], which could be due to confusion by the respondents, as some households with other primary heating systems (e.g., gas boilers or heat pumps) also have electric hot-water storage tanks. In such cases, respondents may have mistakenly identified the hot-water unit as an electric boiler. Regarding the age of the current heating system, the majority of the respondents reported installations between 1 and 6 years ago, with another substantial portion reporting systems older than 10 years. In terms of regional representation, there is a decent representation of most regions of the UK, with a slight under-representation of Northern Ireland and, to a lesser extent, the North East of England. As for the property type and age, there is a good representation of the typical housing stock as well as good coverage of different construction periods. In terms of property size, most properties in the survey fall between 70 and 200 m^2, with good coverage of the up to 70m^2 as well as 201–500 m^2 property ranges. Properties with larger floor areas are comparatively less represented,

Table 7
Summary of attributes and levels in the SP design on ownership and control.

Attribute name (unit)	Explanation provided to the respondents	Number of levels	Source
Upfront cost (£)	One-off investment cost, including equipment and installation.	3	The full ownership option followed the equipment cost from SP2. The shared ownership cost was reduced to 55% of the full ownership cost. There is no upfront cost for the service-based option.
Annual cost of operation (£ per year)	Typical annual heating cost (and equivalent per month cost).	3	The full and shared ownership options followed the running costs from SP2. The value for service-based option was estimated as the sum of operation cost for full/ shared ownership and the upfront cost amortised over 10 years, i.e., 120 months, i.e. assumed longevity of the heating appliance ([55]; [56]) and uplifted by up to 30% premium, i.e. approximate order of magnitude of typical margins in the HVAC sector [57], diminishing with length of the contract, at 5% per year, to ensure the minimum 5% is achieved for the longest, 5-year long contract.
Contract length (years)	Number of years of contractual binding to a specific heating service provider and service.	3	The full ownership option does not have a contract length as the owner is free to operate their heating as they wish. The shared ownership values were assumed at two levels: 2 and 4 years. The service-based contracts were assumed to last as much as up to 5 years. The values were informed by [58] and (Zoe [59]).
Energy pricing	Whether the price of energy used for heating is fixed or varies during the day, and how far in advance information about the energy prices is provided.	3	Three levels assumed: 1. Prices constant across hours and days. 2. Prices can change during the day with 24 h' notice 3. Prices can change during the day with 1 h notice
Control and service flexibility	Whether the operator can switch off the heating for 1 h once a month (after informing the end-user ahead of time), and the compensation for that.	3	Three levels assumed: 1. Respondent controls the heating entirely. 2. Heating can be switched off for 1 h a month. Notification 7 h ahead. Compensation of £14. 3. Heating can be switched off for 1 h a month. Notification 1 h ahead. Compensation of £14.

Table 8
Characteristics of the survey sample, including key attributes of respondents' households: heating system type and age, regional distribution, property type and construction period, and usable floor area. Self-reported by the respondents.

	Wave 1		Wave 2		
Primary heating source	Count	% of Wave 1	Count	% of Wave 2	% of Wave 1
Gas boiler	874	85.1	502	57.44	89.48
Electric boiler	63	6.13	19	30.16	3.39
Electric radiators	26	2.53	5	19.23	0.89
Air-source heat pump	19	1.85	11	57.89	1.96
Storage heaters	13	1.27	6	46.15	1.07
District heating	6	0.58	1	16.67	0.18
Ground-source heat pump	3	0.29	2	66.67	0.36
Other, please specify	23	2.24	15	65.22	2.67
Current heating system age					
Less than 1 year ago	74	7.21	34	45.95	6.06
1–3 years ago	222	21.62	106	47.75	18.89
4–6 years ago	221	21.52	115	52.04	20.5
7–10 years ago	151	14.7	92	60.93	16.4
10+ years ago	290	28.24	189	65.17	33.69
I'm not sure	69	6.72	24	34.78	4.28
UK region					
East of England	93	9.06	56	60.22	9.98
East Midlands	73	7.11	32	43.84	5.7
Greater London	156	15.19	73	46.79	13.01
North East	43	4.19	27	62.79	4.81
North West	120	11.68	64	53.33	11.41
Northern Ireland	14	1.36	6	42.86	1.07
Scotland	97	9.44	52	53.61	9.27
South East	135	13.15	79	58.52	14.08
South West	75	7.3	40	53.33	7.13
West Midlands	94	9.15	50	53.19	8.91
Wales	34	3.31	23	67.65	4.1
Yorkshire and the Humber	93	9.06	59	63.44	10.52
Property type					
Flat (incl. apartment)	158	15.38	63	39.87	11.23
Terraced: mid-terraced	155	15.09	92	59.35	16.4
Terraced: end-of-terrace	75	7.3	36	48	6.42
Semi-detached	305	29.7	174	57.05	31.02
Detached	240	23.37	144	60	25.67
Bungalow	82	7.98	45	54.88	8.02
Not sure	1	0.1	0	0	0
Other: please state	11	1.07	7	63.64	1.25
Property construction year					
Before 1919	110	10.71	84	76.36	14.97
Between 1919 and 1944	138	13.44	104	75.36	18.54
Between 1945 and 1964	121	11.78	76	62.81	13.55
Between 1965 and 1980	158	15.38	90	56.96	16.04
Between 1981 and 1990	88	8.57	55	62.5	9.8
Between 1991 and 2010	162	15.77	96	59.26	17.11
After 2010	110	10.71	43	39.09	7.66
Not sure	20	1.95	13	65	2.32
Property useable floor area					
Up to 70 m^2 (750 ft^2)	67	6.52	32	47.76	5.7
71–100 m^2 (751–1080 ft^2)	179	17.43	86	48.04	15.33
101–150 m^2 (1081–1620 ft^2)	218	21.23	128	58.72	22.82
151–200 m^2 (1621–2160 ft^2)	129	12.56	69	53.49	12.3
201–500 m^2 (2161–5400 ft^2)	78	7.59	38	48.72	6.77
Above 500 m^2 (5400 ft^2)	14	1.36	8	57.14	1.43
Not sure	342	33.3	199	58.19	35.47

though this reflects their relatively small share of the housing stock, mostly among the detached segment [64]. 'The relatively high share of respondents who were 'not sure' about the usable floor report floor area stems from the conventional reliance in the UK on the 'number of bedrooms' as typical, even if informal dwelling size metric. In the modelling exercises, the effective proxy is therefore number of total room as well as property type, which jointly capture the overall size effect.'

3.3. Discrete choice modelling

In the current experimental setting, every respondent was shown 6 separate choice scenarios for each of the SP exercises outlined in Section 3.1, which means that overall, 18 choices were made. This means that responses by the same respondent are not entirely independent and could be characterised by presence of correlation in the error terms. To account for such a possibility, 3 mixed logit models were built for the 3 SP exercises, respectively. The mixed logit model has been known for its flexible formulation that overcomes key limitations of the standard logit choice model by allowing for random taste variation, unrestricted substitution patterns and correlations in unobserved factors over time [65]. Mixed logit models have also been widely used to analyse consumers' preferences [29,34,66].

In this context, we specify the utility of person n from alternative option j (e.g., the specific heating technology, retrofit option or control and ownership arrangement) in choice scenario $t = [1, \ldots 6]$ as:

$$U_{njt} = ASC_j + \beta_{x-n} \bullet X_{njt} + \beta_{c-n} \bullet C_{\mathrm{n}} + \beta_{S-n} \bullet S_n + \eta_{njt} + \varepsilon_{njt}\ , \quad (1)$$

where ASC is the alternative specific constant, X the attributes of the alternatives in choice scenarios, C the contextual variables such as socio-demographics and property characteristics, S the statement variables, β the users' sensitivity to variables, ε the error term and η the error of panel effects, which is assumed to be normally distributed. In particular, as a result of each respondent facing 6 scenarios per SP experiment, all three discrete choice models include a panel effect on the alternative specific constant (ASC): an individual level random error term (normal distribution, integrated out via simulation) that captures unobserved respondent specific effects and accounts for intra respondent correlation across repeated choice observations. This is the only random component in each model. None of the attribute level parameters are specified as random.

During model estimation, various specifications were explored, including data transformations (e.g., categorical variable "floor area" can be transformed into a numerical variable if a linear impact can be expected) and inclusion of alternative- or segment-specific parameters. The inclusion of a variable in the model was dictated by its interpretability (consistent with the practice in discrete choice modelling, only variables supported by a clear theoretical rationale were retained) and any improvement in the model's overall goodness-of-fit. To arrive at the final specification for each model, we conducted extensive testing starting from a baseline naïve MNL model and progressively testing alternative parameter structures across all three models. In parallel, we monitored stability of the parameter estimates and ensuring robustness via repeated estimations using different estimation starting points and see values (for simulation). The models waere estimated using Python Biogeme 3.2.14, employing Monte Carlo integration with 1000 random draws to approximate the choice probabilities [67].

4. Results

This section presents the model results and the accompanying analysis. The provided tables report all attributes of the alternative options but only display contextual and statement variables with statistically significant impacts in order to preserve conciseness and readability given the large number of variables. Model fit was assessed using several standard criteria commonly applied in discrete choice modelling. Specifically, the initial log-likelihood (LL0) and the final log-likelihood (LL) were reported to capture the improvement in fit achieved by the estimated model relative to the null model. The adjusted ρ^2 was used as a goodness-of-fit measure, with higher values indicating better explanatory power. In addition, the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were calculated, where lower values indicate a more parsimonious specification. Statistical significance is denoted as $^{**}p < 0.05$, and $^{***}p < 0.01$.

4.1. Heating technology choice model

Table 9 presents the results of the mixed logit model for heating technology choices. The goodness of fit is acceptable (adjusted $\rho^2 = 0.19$), indicating that the tested variables are important in explaining the choice behaviour. The significant panel effect error component (H2 boiler: 1.37***, Heat pump: 1.5***) indicates that responses made by the same individual are correlated, reflecting the presence of some unobserved factors. No effect concerning the presentation order of the alternatives was observed.

Among the attributes of the alternatives, the sensitivity to monthly costs, when accounting for differences in the units, is similar to fixed costs, consistently with the findings by Meles et al. [27]. For instance, in the case of the heat pump, the coefficient for monthly cost (£00s) is −1.38, whereas the coefficient for fixed cost (£000 s) is −0.195. Financial support schemes, even with a non-zero interest rate, are associated with an increased preference for the technology for which they are available (interest-free loan: 0.193***, 4% loan: 0.165***). This is consistent with the expectations and the results of Mahapatra and

Table 9
Heating technology choice (SP1) model results.

Parameters	Value (**:$p < 0.1$; ***:$p < 0.05$)		
	Gas boiler	H_2 boiler	Heat pump
Alternative-specific constant (ASC)		−3.03	−2.45
Panel data: error term		1.37***	1.5***
Alternative option order (gas-h2-pump)	−0.0214 (generic coefficient)		
Attributes in Alternatives			
Fixed cost (£, 000 s)	−0.213	−0.0899	−0.195***
Monthly cost (£, 00s)	−0.695***	−0.457***	−1.38***
Support: interest-free loan	0.193*** (generic coefficient)		
Support: 4% loan	0.165*** (generic coefficient)		
Maintenance visits	0.0486 (generic coefficient)		
CO_2 emissions (10^4 kg)	−0.128	−4.19**	−1.47
Attitude and statement			
Prevent environmental pollution		0.364***	0.416***
Affordable bills and maintenance			0.394***
Clear about the disruption			−0.248***
Buy less carbon-intensive food			0.246***
Reduced waste and increased recycling		0.267***	0.507***
Property characteristics			
Gas boiler as primary heating source			−1.19***
EPC rating: C (reference: lower rating)			0.828***
Property built between 1981 and 1990 (reference: after 2010)		1.38***	
Number of all rooms listed			−0.132***
Total cost of inspections and services over the past two years: up to £200 (reference: no cost)		−0.682***	−0.546***
LED ownership		0.584***	0.829***
Socio-demographics			
Number of people aged 65 +			0.579***
Annual income: £25,000–49,999 (reference: above £50,000)		−0.684***	−0.759***
High school education			0.979***
Number of observations (individuals / responses)	561/3370		
Initial log-likelihood	−3260		
Final log-likelihood	−2500		
AIC	5290		
BIC	5910		
Adjusted Rho2	0.19		

Gustavsson [20]. As for attention to CO_2 emissions is only marginally significant when evaluating H_2 boilers (−4.19**), in contrast to findings by Wall and Laing [31]. However, in the present study, the sample is substantially larger and more representative. Our findings indicate a lesser role of the heating technology's emissions in determining its attractiveness to consumers. Similarly, the number of maintenance visits was not found to matter, which could be attributed to the low frequency of maintenance overall, occurring once or twice per year. On the contrary, explicitly highlighting the disruption of heat pump installations appears to reduce their attractiveness (−0.248***).

As for attitudes, we observe that people with stronger biospheric values (e.g., "Prevent environmental pollution") (H2 boiler: 0.364***, Heat pump: 0.416***) and more environmentally friendly lifestyles, such as consuming less carbon-intensive food (Heat pump: 0.246***), tend to prefer low-carbon heating technologies. Individuals who perceive low-carbon heating to have affordable energy bills are also more likely to choose heat pumps (0.394***).

The presence of an existing gas boiler reduces the likelihood of installing heat pumps (−1.19***), highlighting both inertia and a preference for gas boilers. This inertia has previously been linked to a preference for familiarity [68]. Properties with a relatively low energy performance certificate (EPC) rating of C show preference for heat pumps (0.828***) and those built between 1981 and 1990 show preference for H2 boilers (1.38***). This difference in preference may be because heat pumps are more efficient and readily available, while H_2 boilers are easier to install in older properties with limited space. The number of different types of rooms in the property is negatively associated with the preference for heat pumps (−0.132***). This reason could lie not just in the higher costs and uncertainty around comfort levels, but possibly also the expected level of disruption during installation (as per the earlier observation). Interestingly, people who have already invested in inspections and services (up to £200) are less likely to switch to low-carbon heating technologies (H2 boiler: −0.682***, Heat pump: −0.546***), which could stem from their satisfaction and low inspection costs of their current heating systems. Lastly, ownership of LED lighting, possibly a proxy for an eco-friendly lifestyle, is associated with higher preference for low-carbon heating technologies (H2 boiler: 0.584***, Heat pump: 0.829***), aligning with the impacts of other environmentally conscious behaviours.

As for the role of socio-demographic factors, the results indicate that households with a higher number of senior adults (0.579***), as well as those including individuals with a high school education (0.979***), have a higher preference for heat pumps. At the same time, we observe that lower annual income hinders the switch to low-carbon heating technologies (H2 boiler: −0.684***, Heat pump: −0.759***), most likely due to the expected expenditure associated with the transition.

4.2. Property retrofit model

Table 10 presents result of the retrofit model estimation. Here, we observe a larger number of non-trading responses where participants consistently chose one alternative regardless of attribute levels. Specifically, 28% of participants always chose "no retrofit" and 26% of participants always chose "minor retrofits". This indicates a preference for these two alternatives as they involve less costs and limited disruption. These non-trading answers are noted and then removed to accurately capture the impact of other factors. This adjustment, however, reduces the statistical power of the model and limits the strength of inference concerning the significance of model parameters.

Similarly to the previous model, the panel effect errors remain significant (Minor: 0.606***, Major: −0.0257***), indicating presence of unobserved heterogeneity leading to correlated error terms across responses from the same individuals. Among attributes of the alternatives, retrofit cost and payback time are the key choice determinants. In particular, a higher retrofit cost reduces its attractiveness (Minor: −25.4**, Major: −0.552**), which is intuitive. As for the payback time, we observe that for minor retrofit measures, a longer payback time reduces its attractiveness as customers often require benefits to be realised quickly (−5.13***). Interestingly and somewhat counterintuitively, this effect is reverse for major retrofit measures (0.564**), where a longer payback time tends to be associated with higher attractiveness. One possible explanation is the presence of unobserved perception concerning lack of trust in major investments that lead to 'quick wins'. This would follow observation of Alberini et al. [69] who reported that implicit discount rates for long term investments in home renovations could be as low as 1.5% and realised over 20–40 years. Similarly, Lakić et al. (2021) noted that people might give more importance to future energy savings when faced with high upfront costs. Also the findings of Schäfer and Hennig [70] indicate the possibility of trusting more in traditional approaches towards home improvement characterised by long-term payouts, compared to what may be seen as short term gains promised by technological novelties, in a behaviour they characterise as 'technical scepticism'. Other factors, such as equipment costs, nuisance, monthly savings and financial support schemes, show no significant association. This is in contrast to findings from Liu et al. [34].

As for attributes, respondents with strong biospheric values prefer minor (Prevent environmental pollution: 0.265***, Respect nature: 0.313***) and major retrofit options (Sustainable travel habits: 0.299***) over no retrofit, highlighting their commitment to environmental conservation. However, those who strongly agree with waste reduction and increased recycling show a lower preference for major retrofits (−0.426***). A possible explanation could be that major

Table 10
Property retrofit choice (SP2) model results.

Parameters	Value (**:p < 0.1; ***:p < 0.05)		
	No retrofit	Minor retrofit	Major retrofit
Alternative-specific constant (ASC)		2.05	−0.568
Panel data: error term		0.606***	−0.0257***
Attributes in alternatives			
Equipment cost (£M)	15.9 (generic coefficient)		
Retrofit cost (£, 0000 s)		−25.4**	−0.552**
Nuisance (days)	−0.00524 (generic coefficient)		
Monthly saving (£, 00s)	1.35 (generic coefficient)		
Payback time (10s of years)		−5.13***	0.564**
Support: interest-free loan	−0.0791 (generic coefficient)		
Support: 4% loan	0.13 (generic coefficient)		
Attitudes and statement			
Prevent environmental pollution		0.265***	
Respect nature		0.313***	
Reduced waste and increased recycling			−0.426***
Sustainable travel habits			0.299***
Property characteristics			
Heating system built 1–3 years ago (reference: less than 1 year ago)			−1.89***
Floor area, 101–150 m^2 (reference: less than 100 m^2)		−0.864***	
Floor area, 151–200 m^2		−0.933***	
Floor area, 200+ m^2		−0.702***	
Property built between 1945 and 1964			1.86***
Fixed price tariff		−0.676***	
Variable price (standard tariff)			−0.895***
Total cost of inspections and services over the past two years: up to £200 (reference: no cost)		−0.528***	−0.996***
Socio-demographics			
Number of people aged 13–17		0.885***	
Master's degree			1.42***
Number of observations (individuals / responses)	244/1460		
Initial log-likelihood	−1470		
Final log-likelihood	−1220		
AIC	2720		
BIC	3200		
Adjusted Rho2	0.073		

retrofitting may be perceived as generating more substantial waste, although this interpretation warrants further research.

Major retrofits are less favoured if the current heating system has been installed in the last 1–3 years (−1.89***), presumably because such modern systems are more likely to have been accompanied by retrofits already. Properties with larger floor areas (>100 m^2) pose barriers to minor retrofits (Floor area 101–150 m^2: −0.864***, 151–200 m^2: −0.933***, 200+ m^2: −0.702***), as they probably usually involve higher costs and greater disruption. Properties built between 1945 and 1964, compared to those built after 2010, tend to prefer major retrofits (1.86***), possibly due to their ageing infrastructure and high energy inefficiency.

Households on fixed tariffs appear less concerned about minor retrofits (−0.676***) and those on variable tariffs (standard tariffs) show less interest in major retrofit (−0.895***), possibly seeking to realize the benefits from differences in pricing more than efficiency gains. Properties are less likely to pursue further retrofits if they have already invested up to £200 in inspections and services (Minor: −0.528***, Major: -0.996***). This is in line with expectations that repeated maintenance-related expenses and activities, including retrofitting, can be both frustrating and disruptive.

As for the household composition, the presence of teenagers in the property is associated with an increased preference for minor retrofits (0.885***), as parents tend to prioritise the thermal comfort of their children. Lastly, higher level of education (i.e., a master's degree) (1.42***) is also associated with a higher preference for major retrofitting, probably due to higher environmental awareness and understanding of the long-term benefits from such investments. Overall, the results appear to be in line with those previously reported by Meles et al. [27].

4.3. Ownership and control choice model

In the third SP scenario concerning ownership and control choice, almost a third (32%) of participants consistently chose “Full ownership” across all scenarios regardless of the varying attributes, demonstrating a clear preference for this traditional ownership model. In contrast, the negative coefficient of the alternative-specific constant (ASC) for the “service-based” option indicates a general reluctance to select this novel service when all other factors are equal.

As shown in Table 11, preference heterogeneity is manifested through the significant panel effect error coefficients (Shared ownership: 1.98***, Service-based: 2.76***). Consumers are more sensitive to monthly costs (£, 00s: −1.41***) than to upfront costs (£, 0000 s: −1.63***), aligning with preferences observed in the heating technology choice model. In addition, participants prefer alternatives with short contract lengths (−0.121***), likely valuing the flexibility to opt-out. Parameters of dynamic pricing (24 h notice: −0.324***, 1 h notice: −0.365***) and DSR switch-off events (notification 7 h ahead: −0.32***, −0.63*** and − 0.471***, 1 h ahead: −0.288***, −0.925*** and − 0.569 ***) are negative, which is not surprising given their potential to disrupt daily routines. Although the coefficients of dynamic pricing and switch-off events vary depending on the notice period, results from the Wald test show that these differences are not statistically significant. Nonetheless, the monthly willingness to accept for these two attributes are calculated and discussed in the next section.

Participants who strongly agree with preventing environmental pollution tend to prefer shared ownership (0.385***), while those with high egoistic values (i.e., “have control over others” -0.368*** and “Be influential” 0.408***) appear to show inconsistent preferences for service-based.

The property characteristics indicate that participants in London are more likely to choose shared (1.12***) and service-based ownership (1.98***), possibly due to the higher prevalence of shared economy and service offerings in the city. Additionally, participants who have spent less than £500 on inspections and services over the past two years (1.42***) are more likely to choose shared ownership. One potential reason involves reduced maintenance responsibilities, which aligns with their previous behaviours.

In terms of socio-demographics, households with three or more employed people (0: −2.06*** and − 1.96***, 1: −2.52*** and − 1.64***, 2: −1.61***), adults (−0.869***), and senior adults (−1.45***) are less likely to choose novel shared and service-based ownership models. In contrast, participants with high education levels, such as those with bachelor's (1.31***) and master's degrees (1.5***), are more open to adopting these new services.

Table 11
Ownership and control choice (SP3) model results.

Parameter	Value (**:p < 0.1; ***:p < 0.05)		
	Full ownership	Shared ownership	Service-based
Alternative-specific constant (ASC)		−1.34	−4.69**
Panel data: error term		1.98***	2.76***
Attributes in alternatives			
Upfront cost (£, 0000 s)	−1.63*** (generic coefficient)		
Monthly cost (£, 00s)	−1.41*** (generic coefficient)		
Contract length	−0.121*** (generic coefficient)		
Changeable electricity price (24-h notice)	−0.324*** (generic coefficient)		
Changeable electricity price (1-h notice)	−0.365*** (generic coefficient)		
Switched off event (notification 7 h ahead)	−0.32***	−0.63***	−0.471***
Switched off event (notification 1 h ahead)	−0.288***	−0.925***	−0.569 ***
Attitude and statement			
Prevent environmental pollution		0.385***	
Have control over others' actions			−0.368***
Be influential			0.408***
Property characteristics			
Greater London		1.12***	1.98***
Total cost of inspections and services over the past two years: £200–500 (reference: not sure and £500+)		1.42***	
Total cost of inspections and services over the past two years: no cost		1.02***	
Socio-demographics			
Number of employed people: 0 (reference: 3 and more)		−2.06***	−1.96***
Number of employed people: 1		−2.52***	−1.64***
Number of employed people: 2		−1.61***	
Number of people aged 18–64		−0.869***	
Number of people aged 65+		−1.45***	
Bachelor's degree			1.31***
Master's degree			1.5***
Number of observations (individuals / responses)	561/3370		
Initial log-likelihood	−2840		
Final log-likelihood	−2430		
AIC	5160		
BIC	5810		
Adjusted Rho2	0.092		

4.4. Willingness to pay (all models)

The results of the discrete choice modelling presented in the previous sections allow for the estimation of the individuals' willingness-to-pay (WTP) for particular attributes (Table 12). Note that a negative value of WTP, sometimes called willingness to accept, indicates that the respondent needs to be compensated the amount to accept the attribute. WTP values are calculated by dividing coefficients associated with each specific attribute by the monthly cost coefficient, each representing the respective marginal (indirect) utility.

The technology choice experiment (SP1) provides estimates of the value attached by individuals to presence of interest-free and 4% loans.

Table 12
Estimates of WTP (incl. 95% confidence intervals) resulting from the technology, retrofit and ownership choice experiments.

Technology choice experiment (SP1)	Gas boiler	H2 boiler	Heat pump
Valuation of the presence of interest-free loan (monthly value)	£27.77 ± 10.07	£42.23 ± 14.93	£13.99 ± 5.41
Valuation of the presence of 4% loan (monthly value)	£23.74 ± 9.30	£36.11 ± 14.24	£11.96 ± 4.90
WTP maintenance visit reduction (monthly value per visit)	£6.99 ± 7.88	£10.63 ± 12.33	£3.52 ± 3.95
WTP CO2 emission reduction per tonne	£1.84 ± 20.19	£91.68 ± 56.07	£10.65 ± 9.43
Retrofit choice experiment (SP2)	**No retrofit**	**Minor retrofit**	**Major retrofit**
Valuation of the presence of 4% loan	–	£51.18 ± 73.49	£2355.07 ± 3444.39
WTP nuisance (per day)	–	-£2.06 ± 3.25	-£94.93 ± 155.41
Ownership choice experiment (SP3)	**Full ownership**	**Shared ownership**	**Service-based**
WTP ownership model value compared to full ownership (annual value)	*Reference*	-£95.04 ± 149.72	-£332.62 ± 216.90
WTP contract length (annual value)	-£102.98 ± 252.91	-£102.98 ± 252.91	-£102.98 ± 252.91
Monthly WTP changeable electricity price (24-h notice)	-£22.98 ± 51.90	-£22.98 ± 51.90	-£22.98 ± 51.90
Monthly WTP changeable electricity price (1-h notice)	-£25.89 ± 54.45	-£25.89 ± 54.45	-£25.89 ± 54.45
Per hour WTP for reduction in advance notice regarding electricity price change	-£0.13	-£0.13	-£0.13
Monthly WTP switched off event (notification 7 h ahead, direct compensation £14)	-£22.70 ± 70.17	-£44.68 ± 105.37	-£33.40 ± 93.17
Total compensation for a switched off event (notification 7 h ahead)[1]	-£36.70 ± 70.17	-£58.68 ± 105.37	-£47.40 ± 93.17
Monthly WTP switched off event (notification 1 h ahead, direct compensation £14)	-£20.43 ± 64.51	-£65.60 ± 136.05	-£40.35 ± 104.29
Total compensation for a switched off event (notification 1 h ahead)[1]	-£34.43 ± 64.51	-£79.60 ± 136.05	-£54.35 ± 104.29
Per hour WTP for reduction in advance notice regarding DSR event	£-0.38	-£3.49	-£1.16

[1]Includes WTP estimate and the direct compensation of £14 assumed in the scenario

In particular, the presence of such schemes corresponds to an implied acceptance of additional costs between about £20 and £30 costs for gas boilers, £10–20 for air-source heat pumps and £35–45 for hydrogen-ready boilers. As for the maintenance visit reduction, the WTP for a reduced number of maintenance visits is in the range of about £3–11. The willingness to pay for reduced CO_2 emissions varies from around £1.84 per tonne in the case of gas boilers, to much higher values of £10.65 for heat pumps and £91.68 for hydrogen boilers. While these differences are large, all of these values are in line with variations reported in the literature [29], which shows substantial spread in how people perceive and trade off costs against carbon emission reductions.

When interpreting these results, it is important to note that gas boilers and heat pumps are already commercially available options, while fully hydrogen-ready boilers are not yet available (only "hydrogen-blend ready" allowing for up to 20% hydrogen). Their technological trajectory and policies around hydrogen heating are still uncertain, as is the hydrogen supply and associated emissions and costs. These aspects were not considered in the survey beyond the considered cost levels but may affect the stated preferences.

In the retrofit context, the presence of a 4% loan has substantial value. In particular, for major retrofits, its effect is equivalent to households receiving as much as £1400 in additional financial support. As for nuisance reduction, the respondents value the ability to reduce the retrofit duration by a day at about £2 and £94 for minor and major retrofits, respectively.

The SP3 experiment yields several interesting results in terms of the value attached by individuals to flexible service operation. Firstly, the WTP values for shared ownership and service-based operation equate to ca. £95 and £330, respectively, indicating the average value of the benefits the customers would expect as a result of moving away from full ownership models. Regarding the contract length, each additional year of contractual commitment would need to yield at least ca. £85 in monetary benefits. As for the dynamic electricity price, the monthly compensation estimates are on average equal to £22.98 and £25.98 for the 24-h and 1-h notice periods, respectively. Assuming linear interpolation, this implies that the reduction in notice period requires compensation of ca. £0.13 per each hour.

Lastly, the respondents indicated their preferences for accepting DSR switch-off events (up to 1 h per month, with a direct compensation of £14). The acceptance differs across ownership models and notification periods. In particular, for the full ownership model, the additional compensation required to the stated £14 is equal to £22.70 and £20.43 for 7 and 1 h notification periods, respectively. This brings the total expected compensation values to £36.70 and £34.43, respectively. Although this pattern may appear surprising, since longer notice would typically be expected to reduce the required compensation, the width and overlap of the respective confidence intervals indicates that these values are not statistically different from one another. In the case of the remaining ownership models, the estimated values are equal to £44.68 and £65.60 (shared ownership) and £33.40 and £40.35 (service-based) for 7 and 1 h notification periods, respectively. When including the promised £14 of the expected compensation, this brings the total to £58.68 and £79.60 (shared ownership) and £47.40 and £54.35 (service-based), respectively. Again, interpolating linearly between the values provides an estimate of £3.49 and £1.16 per 1 h DSR notice reduction (under the current scenario) for the shared ownership and service-based models, respectively.

5. Discussion

An understanding of the drivers and barriers of low-carbon heating technology adoption remains paramount in the context of meeting the decarbonisation targets. The present analysis provides a unique perspective, considering jointly the choice of technology, retrofit, as well as ownership and operation.

In the analysis of heating technology choice, it was revealed that the take-up of low-carbon heating options tends to be driven not just by upfront investment cost and monthly cost, but also by contextual factors: property characteristics, occupancy status and individual attitudes and perceptions. The burden of cost can be influenced through support schemes, including grants and loans, which can reduce the perceived cost, e.g. by £42.23 ± 14.93 and £13.99 ± 5.41 for interest-free loan for H2 boiler and heat-pump respectively (cf. Table 12). Still, the trust in technology, perception of reliability and expectation of disruption require careful consideration of communication strategies aimed at the public. The current results indicate that gas boiler is, keeping all other parameters constant, the preferred technology choice (ASCs are −3.03 and − 2.45 for H2 boiler and Heat pump respectively).

More concretely, measures aimed at the upfront cost, such as Boiler Upgrade Scheme (BUS) in the UK, do not tackle the running cost concern of households for electricity, which means they do not address the uncertainty around medium- and longer-term electricity prices. Given that the present results indicate *both* cost components to matter when choosing between heating technologies (SP1: the coefficient for monthly cost (£00s) is −1.38, the coefficient for fixed cost (£000 s) is −0.195), unless the ongoing running cost of heat pumps (primarily electricity) can be addressed, adoption of low carbon heating alternative ends up being

a ‘hard sell’. Therefore, it should be a political priority to reduce electricity costs for heat pumps in order to facilitate decarbonisation. In line with this, there is an ongoing review performed in the UK by the energy regulator (Ofgem) considering how energy costs are recovered and allocated across different consumers, based on the current system of standing and variable charges [71]. The considered schemes include shifting the weight of infrastructure cost recovery from standing charge to variable consumption, progressive pricing (income based) and rebalancing environmental levies from power to gas to make heat pumps cheaper to run. The present analysis may serve as a starting point to measure how effective such schemes are likely going to be at impacting low-carbon heating adoption, and what welfare implications they are likely going to cause among different consumer segments.

In addition to the above, the results demonstrate how the relatively small impact of carbon emissions on the choice of heating technology compared to cost components or expectation of disruption: WTP for CO2 emission reduction was not different from 0 for natural gas, characterised by very wide confidence interval for the heat pump and only yielding statistically significant result for the most hypothetical alternarive. This points towards a role of innovative, market-based incentives financially rewarding consumers for low-carbon technology choice and flexible consumption, as the benefit of reduced emissions alone is not sufficient to sway the technology choice. One example is Octopus' Zero Bills Homes initiative (Octopus [72]), based on fully equipped ‘net zero’ homes where residents receive a special tariff guaranteeing no energy bills in exchange for generating, storing and selling electricity to the Octopus to trade and cover costs when needed. Thus, the findings confirm the need to refocus communication of the benefits of low-carbon heating technologies towards outcomes that are directly observable and measurable by households.

At the same time, the observed inertia around the use of natural gas boilers (recall the aforementioned ASCs) may be a phenomenon whose effect may reduce over time. In particular, building standards increasingly mandate low-carbon heating technologies, which contributes towards experiencing the benefits of such technologies, and evolving their overall perception among the public. There is a parallel in the Electric Vehicle (EV) take-up, where ‘word-of-mouth’ plays a substantial role in purchasing decisions [73,74]. Thus, the demonstrated role of attitudes in choosing low-carbon heating options (e.g. SP1: intention to prevent environmental pollution, buying less carbon-intensive food, reducing waste and increasing recycling) justifies initiatives that let people personally experience such technologies, shaping their views, contributing to word-of-mouth communication and overall public perception.

Beyond the technology choice, the results shed light on the retrofit preferences. Specifically, the minor retrofit option, characterised by limited disruption and affordable cost (especially with support schemes) and clearly measurable benefits for households (whilst also having environmental benefits, even if not articulated in the SP outline) was preferred by the majority of individuals (ASC of 2.05 vs. -0.568 for the major retrofit). The latter also indicates that individuals are willing to tolerate temporary nuisance when there is sufficient payback. This observation should inform policy design of low-cost financing support for low-cost, high-impact retrofits or even specific financing schemes aligned with heat pump or more broadly low-carbon heating switches. Major retrofit, at the same time, is clearly not something favoured by the individuals upfront. In our WTP analysis, each day of nuisance associated with retrofit works was valued at ca. £95 (compared to £2 for minor), though with a broad confidence interval (95% is £155.41) that suggests substantial heterogeneity among the consumers. This also highlights that expected benefits of such investments must be substantial, tangible and spread over long term to make it an acceptable option.

Turning to the third aspect of low-carbon heating adoption – the ownership and operation model, we observe that full ownership and control remains the preferred option (ASCs of −1.34 and − 4.69 for the shared-ownership and service-based models and an estimated willingness to pay of -£95.04 ± 149.72 and -£332.62 ± 216.90, respectively), with individuals expecting to see meaningful benefits to be willing to sacrifice their autonomy over the operation of their heating systems. Exploring this observation, to the extent permitted by the boundaries of the SP experiments, the current analysis confirms the feasibility of acceptance of different ownership models alongside variable electricity pricing and DSR events as means of reaching national heating decarbonisation targets. This is reflected in SP3, where we indeed observed negative sentiment towards chaging electiricty prices or presence of DSR event, but also noted *acceptance* of such conditions with suitably set rewards. While our DSR setting assumed a comparatively substantial reward for participation in a DSR event (ca. £14), we intended to show its feasibility in a more welfare-sensitive context of heating, rather than postponement of appliance use. This finding provides evidence towards the possibility of incorporating DSR into heating offerings, which could help offset the aforementioned costs of adoption.

The study provides a range of WTP (and compensation) estimates that can serve as inputs into tariff design, policy frameworks and new business models for low-carbon heating provision. For example, we observe high standards for accepting shared ownership and service-based offerings (heating-as-a service). Specifically, compared to full ownership, individuals would need to see actual monetary benefit of 95.04 ± 149.72 and 332.62 ± 216.90annually on average to accept shared and service-based model of operation, noting also substantial uncertainty and heterogeneity among the users indicated by the wide confidence intervals. This offers insight into business model opportunities for OEMs who offer monthly financing options and renting solutions. At the same time, such options, alongside shared ownership, can be seen as a means of addressing the current low take-up caused by cost barriers in situations where schemes such as BUS may not be feasible.

Last but not least, we observe that the obtained empirical parameters can serve well for disaggregate (agent-based) modelling and optimisation of heating-related choices. Such tools would be key to test viability and impact of different policy scenarios, such as effectiveness of interest-free vs. 4% loans or the broader impacts on the grid. In particular, we can see applications of approaches such as those discussed by many authors [75–78] to domestic heating contexts. Given the unique availability of three key heating decision aspects: technology, retrofit and operation model, the present empirical findings could help operationalise such models for the UK, providing realistic simulation and policy evaluation toolkit necessary for the effective transition towards low-carbon heating future.

6. Conclusions

The continuing efforts towards decarbonisation require efficient policy mechanisms that acknowledge and actively utilise the broader spectrum of decision contexts concerning residential heating. The present study offers a number of directions towards that end that can be explored by policy-makers in this space.

Consistently with observations elsewhere, both upfront and ongoing costs remain among the key factors affecting the uptake of low-carbon technologies. While grants, loans, shared ownership, and service-based models can tackle the upfront cost burden (assuming the associated contracts are clear and fair), it is the uncertainty surrounding running costs that may hamper adoption of low-carbon forms of heating. This is where targeted tariffs, accompanied by guarantees concerning savings and payback periods, may be essential to mitigate against concerns of unpredictable heating costs. Accompanied by reliable but also relatable information, including case studies, these measures are aimed at building awareness and trust in what often comes across as very novel and disruptive change to people's properties and even lifestyles. Thus, even when individuals care about the decarbonisation objectives, their actual decisions are more likely going to be driven by monetary and everyday life considerations.

Minor retrofits present a substantial opportunity to accompany all new installations. They are acceptable, cost-effective, improve energy

efficiency and provide a means of enhancing the perceived effectiveness of low-carbon heating appliances. Major retrofit initiatives should not be abandoned, however, but they should be framed as significant investments and property upgrades, and supported accordingly.

Low-carbon heating options can also play a role in energy flexibility, offering mutual benefits to users and the grid alike. This is likely a medium- to long-term possibility, given the low maturity of the market and the low level of understanding among members of the public. However, gradual deployment, even on a trial basis, with users permitted to override the events when necessary while having the opportunity to benefit when they can, could be a viable pathway towards building understanding of participation in grid services. For that, clear and transparent contracts, accompanied by awareness-building and education, are certainly essential.

In all of these scenarios, support tailored to user needs is paramount. This will typically encompass not only financial support, but also the provision of suitable advice, assurances, safeguards, and maintenance services for the adopted technologies.

As for limitations of the current study, the results presented here are based on surveys of UK homeowners, with strong overrepresentation of gas boiler owners and using UK-specific policy and cost values. Therefore, translating the results to other countries is not straightforward and should be done very carefully. The UK has a particularly poorly insulated building stock, which likely affects both technology and retrofit choices. It also has a high reliance on natural gas for heating, and a high electricity to gas price ratio, which makes the economics for heat pumps more challenging.

Future studies could explore alternative discrete choice modelling structures, especially joint models across the three decisions (technology-retrofit-ownership/operation). While more challenging from the estimation and sample size points of view, such models could yield more detailed insights on unobserved correlations between these choice dimensions. Similarly, an increased sample size would also provide a means of investigating preferences in more detail within pre-defined segments of interest, e.g. property resident-owners vs. landlords, for which the present study's sample was not sufficient.

CRediT authorship contribution statement

Jacek Pawlak: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Han Wang:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas V. Olympios:** Writing – original draft, Methodology, Investigation. **Matthias Mersch:** Writing – original draft, Methodology, Investigation, Conceptualization. **Aruna Sivakumar:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Arthur Bessis:** Writing – original draft, Investigation. **Christos N. Markides:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Nilay Shah:** 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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