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From policy to practice: The role of national policy instruments and social barriers in UK energy efficiency adoption in households

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ABSTRACT

This paper investigates the adoption trends for energy efficiency (EE) measures in the UK residential sector and the extent to which national-level EE policies impact households' willingness to adopt EE measures and technologies. Using survey data from a representative sample of more than 2000 households across the UK and discrete choice models, this research examines the preferences given to different policy schemes such as tax rebates, grants, loans, easing administrative barriers or information campaigns; and its role on household decisions to adopt EE measures. We find that national-level policies in the form of grants and subsidies, information campaigns on savings and a reduction of administrative barriers would positively impact the probability of a household to adopt such measures. Differences are found between the policy drivers in the adoption of low-cost EE measures e.g. loft insulation vs. High-cost EE measures e.g. heat pumps. Importantly, our results highlight the role of policy mixes in fostering the adoption of EE measures in UK. In combination with other policies, tax credits can be effective in fostering the adoption on EE measures. Our findings have implications for policymakers seeking to enhance the effectiveness of EE policies and address social challenges to promote sustainable energy use.

1. Introduction

The importance of energy efficiency (EE) policies in reducing energy consumption and greenhouse gas emissions has been well established by decision makers and international organisations (IEA, 2019). However, the effectiveness of these policies depends on their ability to influence the behaviour of households, which are responsible for a significant portion of energy consumption (Bertoldi, 2017). In particular, among the OECD countries, the UK is at the top end in regard to energy consumption in households. In 2021, the residential sector accounted for approximately 32% of the total final energy consumption and the use of energy for heating, lighting and powering appliances, in households, represented 18.7% of the total energy consumption in the UK (DBEIS, 2021). Domestic energy consumption increased by 2.2 million tonnes of oil equivalent in 2021 in comparison to the previous year (DBEIS, 2022). Reducing energy demand through greater efficiency can help the UK meets its climate and EE targets, reduce energy bills and fight fuel poverty among other benefits (ICL, 2019). The cost-of-living crisis has accelerated the need to decarbonise the residential sector, and to reduce the energy consumption of households. Energy costs have increased exponentially during the last two years. While the average gas bills fell by 27% between 2014 and 2021, the increases suffered from 2021 took them in 2022 to 31% above the 2014 levels in real terms. From 2021 to 2022 the average gas bill in real terms almost double. Regarding electricity, electricity bills have increased steadily in real terms since 2010 and their 2022 level was 102% higher than in 2010 in real terms (Bolton and Stewart, 2024). The impact of this exponential increase is affecting differently the households in different income deciles in the UK. The average spending on energy per household reaches these days an 8.3% of total expenditures for the lower 10%, 7.7% for the second decile and decreases until 3.3% for the top 10%. In 2022, 13.4% of households in England were in fuel poverty (DESNZ, 2023). These figures call for urgent policy action if the UK government wants to avoid an increase in the percentage of their population at risk of energy poverty but also if it wants to keep alive the net zero target promise for 2050.

A key strategy being recommended is to enhance the energy efficiency of current homes by widely adopting energy-saving practices, improvements and measures (Pettifor et al., 2015). Yet, the UK faces challenges associated to the old housing stock (the oldest in the European continent), that makes more difficult retrofitting for energy efficiency measures (Piddington et al., 2020). In order to promote such adoption and diffusion, the UK government has implemented since the

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early 2000, policy efforts to reduce energy consumption in the household sector. These policy efforts in the UK have taken the form of regulation e.g. building energy efficiency standards; soft instruments and information programmes, e.g. energy labelling; but above all financial and economic measures in the form of subsidies, tax rebates and also white certificates[1]. More recently, the government has announced that the UK will aim to phase out 80% of the UK's gas boilers by 2035.[2]

Most policy interventions have focused on technological innovations to reduce the consumption of energy services provided in households and improve their energy performance. Yet, as aforementioned UK's homes and buildings are among the least efficient in Europe. The case of the UK holds significant interest as it ranks very low in EE across OECD countries with the household sectors suffering the most from the extended recession after the COVID pandemic and the energy price crises that have resulted in increases in energy poverty rates, as aforementioned, to 13.4% of households on energy poverty in England in 2022[3] (Hinson and Bolton, 2024). The UK government's policies have not yet addressed the energy efficiency problems sufficiently, and the country is paying the price for a decade of policy changes and a lack of a stable policy framework in this area. For the UK to fulfil its net-zero ambitions and energy efficiency goals, it will need to adopt a more stable, long-term approach and learn from both international successes and perceived domestic failures to build confidence among consumers and investors (Hodgkin and Sasse, 2022).

In this paper, we examine the extent to which national-level EE policies impact household decisions to adopt EE measures and technologies, i.e. the drivers; and the social challenges that may have hinder adoption, e.g. vulnerable households, lack of information, lack of incentives; in the United Kingdom. Our study aims to inform policymakers on the design of effective policies that can overcome barriers to adoption and promote sustainable energy use. We will focus mainly on barriers associated to heating and on policies oriented to improve energy efficiency in heating uses. Heating i.e., space heating, water heating and cooking represents around 80% of the total energy consumption in households. Also, unlike lighting and appliances, energy efficiency for heating requires bigger investments, electrification and/or changes in infrastructure.

Past studies have focused on the determinants of EE technology adoption in households, yet empirical work on other technology-relevant behaviour for EE improvements remains narrow (Leicester and Stoye, 2017; Mills and Schleich, 2014). Research work focused on the British building sector, on EE technology for heating and, in particular, on policy diffusion issues has also been limited with the exception of few studies (see Howarth and Roberts, 2018; Pelenur and Cruickshank, 2012; Tovar, 2012)

To cover this gap, we use survey data from a representative sample of more than 2000 households across the UK and discrete choice econometric techniques, to examine the preferences given to different policy schemes such as tax rebates, grants, loans, easing administrative barriers or information campaigns; on household decisions to adopt EE measures controlling for households and dwellings' characteristics. Our research expands upon previous work by incorporating a comprehensive array of energy efficiency (EE) measures, providing deeper understanding of the factors influencing their adoption and also the adoption of low-cost vs. high-cost EE measures. This study differentiates itself by utilizing observational survey data to examine household EE measures adoption patterns. Additionally, this study goes beyond the traditional focus on demographic, socio-economic, and property-related factors to include a broader spectrum of variables. Notably, it examines the impact of financial assistance programs and the effect of support mechanisms on the adoption rates of EE measures. We also and importantly analyse the role of policy mixes and the importance in the implementation of combinations of policy instruments to foster the adoption of EE measures at the household level. We conclude that policy combinations are better suited to overcome the multiple barriers faced by citizens when deciding on the adoption of EE measures. We find that national-level policies in the form of grants and subsidies, information campaigns on savings and a reduction of administrative barriers would positively impact the probability of a household to adopt EE measures and technologies. Differences are found though between the policy drivers in the adoption of low-cost EE measures e.g. loft insulation vs. High-cost EE measures e.g. heat pumps. As aforementioned, our results highlight the essential role of policy mixes in fostering the adoption of EE measures in UK households. For example, in combination with other policies, tax credits can be effective in fostering the adoption on EE measures by households. Our findings have implications for policymakers shaping policies aimed at enhancing energy efficiency in homes, which in turn, is critical to achieving the UK's goals for net zero emissions.

The rest of the paper is structured as follows. In the following section, we review the literature on policy instruments for energy efficiency in heating, drivers in adoption and outline the research hypotheses. Section 3 introduces our data, model and methods. Results and robustness checks are summarized and discussed in section 4. Finally, section 5 concludes with some policy implications, limitations and future research directions.

2. Literature review

The adoption of energy efficiency measures in households is an important component of efforts to reduce energy consumption, lower greenhouse gas emissions and promote sustainable living. As the IEA (2019) points out, energy efficiency is the most efficient way of reducing GHG emissions and therefore policies must be implemented to foster the adoption of EE measures in industry but particularly in the residential sector. To encourage the adoption of energy-efficient technologies and practices, a variety of policy instruments have been developed. These policies are broadly categorized into regulatory measures, economic and financial mechanisms, and soft approaches (see e.g. Borrás and Edquist, 2013; de Bruijn and Hufen, 1998; John, 2011; Rogge and Reichardt, 2016; Gillingham et al., 2009). Over time, more nuanced classifications have emerged, particularly for policies aimed at fostering decarbonization efforts and, specially, for policy instruments oriented towards fostering the adoption of more sustainable, cleaner and efficient measures by families and households (See Peñasco et al., 2021 or Della Valle and Bertoldi, 2022 for detailed typologies of policies). However, the effectiveness of these policies varies depending on factors such as household income, education, and attitudes towards energy conservation. Social challenges such as vulnerability, lack of information, and lack of incentives can also hinder adoption, particularly among low-income and vulnerable households.

Regulatory measures, such as mandatory codes and standards, are relevant in setting the legal framework for energy efficiency. For instance, the European Union's energy labeling scheme requires that heating equipment and electrical appliances meet specific efficiency criteria. This policy has been shown to influence consumer behavior by steering choices toward more energy-efficient products (Sammer and Wüstenhagen, 2006). Similarly, building codes that establish minimum energy performance standards can drive significant improvements in building energy efficiency, as seen in different studies (see e.g. Economidou et al., 2020). Additionally, energy-saving obligations tied to market-based mechanisms like white certificates compel utilities to achieve specific energy savings, creating a structured compliance

[1] Also known as renewable energy obligations.

[2] Initially, the UK government announced the banning in the installation of gas boilers in new buildings by 2025 and the banning in the sales of gas boilers to existing homes by 2030. Yet, this decision was reversed in September 2023 by the Prime Minister.

[3] Figures are 24.6% for Scotland (2019), 14% for Wales (2021), 24% for Northern Ireland (2019) (Hinson and Bolton, 2024)

framework that promotes energy efficiency. Under such a system, producers, suppliers or distributors of electricity, gas and oil are required to undertake energy efficiency measures for the final user that are consistent with a pre-defined percentage of their annual energy consumption. While literature is scarcer than for other instruments, the technological effectiveness of this policy i.e. how much they foster deployment, seems to be positive (Lees, 2006, 2008; Mundaca and Neij, 2009).

Economic and financial instruments play a crucial role in addressing the cost barriers associated with energy efficiency adoption. In particular, for the household sector i.e. to influence the purchase habits and adoption of cleaner measures and technologies by the end-user; the majority of instruments fall under the category of fiscal and financial incentives. In particular, we find subsidies and rebates that are financial incentives provided to households for purchasing energy-efficient heating systems or retrofitting homes that can significantly lower the upfront costs of the investment. These financial instruments can be designed in the form of grants, loans and soft loans, or tax rebates. The impact of such measures varies considerably depending on the actual design of the policies (Peñasco et al., 2021). A study by Gillingham and Palmer (2014) on the effectiveness of energy efficiency subsidies in the United States highlighted their role in overcoming financial barriers to the adoption of energy-efficient technologies.

A less used type of instruments for households are Feed-in Tariffs and Performance-based Incentives. These economic tools reward households for the energy savings achieved through efficient heating solutions. While specific studies on their impact are less common, the principle of providing direct financial benefits for energy savings suggests a potentially high impact, as it aligns economic incentives with energy efficiency goals (Bertoldi and Rezessy, 2007; Bertoldi et al., 2009; Eyre, 2013).

Beyond financial barriers, socio-demographic factors also play a significant role in the adoption of energy efficiency measures (Huebner et al., 2015; Wilson and Dowlatabadi, 2007). For example, due to the initial expenses and limitations in accessing credit, lower-income UK households tend to be more hesitant about investing in such technologies (Rosenow, 2013). The studies by Achtnicht and Madlener (2014) and Damigos et al. (2021) highlight the significance of initial investment costs, ongoing savings, and return on investment. Households are more likely to invest in energy-efficient technologies when they perceive the cost savings to outweigh the initial expenses. Furthermore, as aforementioned, financial incentives such as subsidies, tax rebates, and reduced utility rates serve as critical motivators by lowering the financial barriers to adoption. Nevertheless, the effectiveness of these initiatives in encouraging investments and the actual energy savings realized have been subject to debate (IPPR, 2018; Royston et al., 2018; Fowlie et al., 2018).

Based on this evidence, the first hypothesis (H1) proposes that *the implementation of public policies that facilitates the access to information, the adoption and the reduction of upfront costs, increases the probability of adopting EE measures for heating at the household level.*

In addition to financial incentives, informational barriers significantly impact the adoption of energy efficiency measures. Soft approaches, such as informational campaigns and energy audits, aim to raise awareness and provide guidance on energy-efficient technologies. In particular, for the residential sector, the provision of energy audits may be a way to increase awareness among households. Energy audits provide homeowners with professional assessments of energy use and recommendations for improvements that can demystify energy savings and suggest specific actions. While the immediate impact of audits may be considered medium due to their reliance on subsequent homeowner action, their importance in guiding decisions should not be underestimated (Murphy, 2014). Additionally, public awareness campaigns aim to change consumer behaviour and attitudes towards energy efficiency are a tool generally used by governments to promote the adoption of EE measures in households. Their impact varies but is generally categorized as medium. Campaigns that effectively engage consumers, such as the UK's "Act on CO2" initiative, have been successful in raising awareness and encouraging action towards energy efficiency, although they have been hardly used (Kern et al., 2017).

It is noted also that many programs focus solely on financial incentives and fail to consider other factors like social norms or viewpoints towards energy, which can also act as barriers to the uptake of energy efficiency measures (Pelenur, 2018). In particular, bureaucratic regulations and complex policies often pose challenges for homeowners. Obtaining permits, navigating zoning restrictions, and ensuring compliance can be daunting. Policies that reduce the complexity and increase the accessibility of energy-efficient solutions, such as streamlined application processes for incentives and widely disseminated information campaigns, effectively lower the barriers to adoption.

Additionally, lack of awareness about available incentive programs can discourage homeowners from pursuing energy-efficient upgrades. These programs, which offer financial support, remain underutilized due to accessibility issues. The availability, accessibility, and perceived effectiveness of energy-efficient technologies directly influence adoption rates e.g. lengthy permit approval processes delay home renovations, that generally include energy efficiency improvements (Judson and Maller, 2014; Jack et al., 2011). Lastly, homeowners may struggle to find clear information on available options, benefits, and eligibility criteria. Many homeowners remain unaware of the long-term benefits of energy efficiency, including cost savings and improved comfort.

Based on this, the proposed second hypothesis (H2) suggests that *policies oriented to tackle informational and administrative barriers are the most relevant, i.e. soft instruments oriented to the provision of information about schemes and savings and to easing administrative barriers increase the probability of adopting EE measures for heating at the household level to a greater extent than other policies.*

To effectively promote energy efficiency, it is crucial to adopt a comprehensive approach that addresses multiple barriers and leverages diverse motivators (Wekhof and Houde, 2023). Generally speaking, retrofitting existing homes is logistically complex. It requires assessing the structure, coordinating installations, and minimizing disruptions to daily life which necessitates of careful planning (Della Valle and Bertoldi, 2022; Carlander and Thollander, 2023; HOA, 2024). The aforementioned type of policy instruments and preferences could be implemented individually and/or as an array of policies. A successful policy mix should leverage the strengths of each instrument type, tailored to the specific context and needs of the target population, to maximize energy savings and reduce carbon emissions (Rosenow et al., 2016). These include soft instruments like promoting energy efficiency labels and setting minimum-efficiency standards for heating systems and appliances (Gana and Hoppe, 2017). Additionally, governments can provide grants and subsidies for households to adopt energy-saving measures, such as insulation and efficient heating systems (Solà et al., 2021). Tax incentives for the purchase of energy-efficient heating appliances, and the implementation of regulatory instruments to enforce minimum energy efficiency standards for heating equipment (Trotta

Table 1
Descriptive statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
Dependent variables					
EE installed (any)	2084	0.6862	0.4642	0	1
Low-cost EE installed	2084	0.5298	0.4992	0	1
High-cost EE installed	2084	0.5926	0.4915	0	1
Independent variables					
Age dwelling	1944	2.4835	1.1691	1	5
Surface	2084	4.3772	1.8715	1	6
Bedrooms	2065	3.7806	1.0124	1	7
Size	2059	2.2661	1.1568	1	8
Tenure	2084	1.3244	0.5170	1	3
Type housing	1905	2.8462	1.6026	1	6
EPC	2084	7.2668	2.4885	1	9
Move date	2032	5.8784	1.4633	1	7
People >75	2074	0.1090	0.3117	0	1
People <16	2074	0.3187	0.4661	0	1
Region	2084	6.2030	2.9922	1	11
Income	1606	7.2067	3.7404	1	15
Awareness	2084	0.9822	1.2345	0	6
Tax credits pref.	2084	6.6871	2.6238	1	11
Loan pref.	2084	5.3796	2.7973	1	11
Grant pref.	2084	8.2505	2.6314	1	11
Admin barrier pref.	2084	7.3464	2.4965	1	11
Utilities pref.	2084	7.6142	2.7599	1	11
Info. Efficient use pref.	2084	6.3608	2.5440	1	11
Info. Potential savings pref.	2084	6.6080	2.5833	1	11
Info. Support schemes pref.	2084	6.8527	2.5486	1	11
Higher EE standards pref.	2084	6.4587	2.6833	1	11
Stronger EE standards pref.	2084	6.3916	2.6530	1	11

et al., 2018) can complement the mix of policy instruments. Moreover and importantly, governments can focus on awareness creation and education campaigns to encourage households to adopt energy-efficient heating practices (Trotta et al., 2018). They can also develop policies that promote the use of renewable energy sources for heating, such as solar heating systems, and provide support for the installation of these systems in households (Azimoh et al., 2015; Ibrik and Sulaiman, 2019). Additionally, governments can implement smart building energy management systems to optimize heating and cooling operations in residential buildings, thereby improving energy efficiency (Rocha et al., 2015).

Based on this comprehensive understanding, the last hypothesis (H3) proposes that *effective strategies to promote energy efficiency must adopt a holistic approach, addressing multiple barriers and leveraging diverse motivators.*

Additional considerations, such as geographical location and regional climate differences, which result in varying energy demands and costs, also play a role in the suitability and adoption of EE measures (Hamilton et al., 2016; DECC, 2012). Demographic characteristics such as age, income, education level, and household size have been found to affect the likelihood of adopting energy efficiency measures. Neves and Oliveira (2021) and McMichael and Shipworth (2013) indicate that higher income levels often correlate with greater adoption, likely due to increased access to information and financial resources. Cultural factors, including values and lifestyle, also influence perceptions of energy efficiency and the willingness to change consumption habits. As can be derived from the array of policy options available to governments, the adoption of energy efficiency measures in household heating is a complex challenge that requires a multi-faceted policy approach. Regulatory and economic instruments often provide the most direct and significant impact by creating mandatory standards and financial incentives. However, informational instruments and voluntary agreements also play critical roles in raising awareness, providing guidance, and fostering a culture of energy efficiency (Della Valle and Bertoldi, 2022).

3. Data and methods

3.1. Data

We use survey data from a representative sample of more than 2000 households across the UK[4] to examine the impact of national-level policies on household adoption of EE measures and technologies. The field was completed between July and August 2022. The link to the questionnaire is provided in the SI.1 (Box A1). A pilot was implemented with 50 respondents before launching the final survey. We did not observe difficulties and the survey was launched as designed originally. The survey aimed at collecting data and valuable information on the household energy consumption, on the type sources of energy used e.g. gas, electricity, district heating etc., the adoption of any energy efficiency measure and the time of the adoption on top of the more traditional socio demographic and economic characteristics of the households. The survey covered a representative sample of 2084 private households in Great Britain i.e. England, Wales, and Scotland regardless of their size or any other financial or social characteristics. The survey was implemented online through YouGov, an international research data and analytics group headquartered in London, UK. As a prerequisite, the person answering the questionnaire was above 18 years old and responsible for paying the household's energy bills. To the best of our knowledge, this survey is the most recent one performed in order to try to understand attitudes and behaviours related to energy efficiency adoption and energy efficiency policy in the UK in the post pandemic context. Note that the microdata file consists of individual survey responses stripped of identifiers and was handed directly from YouGov to the authors. The descriptive statistics of the variables used in this study are presented in Table 1. A correlation matrix of the covariates can be found as well in the SI.1 (Fig. A1).

3.1.1. Dependent variables

The participants were asked if they have installed an EE measure of interest, as well as additional details in regard to its particularities i.e., year undertaken, costs and if they had used a government programme to help financing the cost etc. The dependent variables for the discrete choice model were thus constructed from participants' responses to the question: *Since you moved to your current address, have you undertaken any of the following EE measures?*

This study assumes that the installation of any EE measures recorded in this study are the only EE measures that have been taken by the dwelling. Given that this is self-reported data we found difficult to control for former adoptions undertaken in any of the buildings. While we control by the current level of the Energy Performance Certificate in each dwelling to have a sense of the energy efficiency levels already existing in the different buildings, this may bring some bias into final results as it disregards the adoption of any form of EE measures installed previous to the current occupant. The final set of dependent variables representing the set of potential EE measures adopted by the occupants

[4] The market research company (YouGov), in charge of collecting the data, ensures the representativity of the sample politically and nationally. The representative sample is obtained by drawing in the respondents from their own panel using active quota sampling. Data is also weighted afterwards to account for any inconsistencies between the sample and national representative quotas. Particularly, YouGov weights their Great Britain (GB) surveys by (1) age interlocked with gender and education, (2) political attention (3) social grade (4) 2019 recalled vote interlocked with region and (5) EU referendum recalled vote. YouGov included some routing within the ad-hoc survey so that only billpayers took the main body of the questions. As there are not publicly available targets for the population of billpayers, this was the best approach. This does mean that e.g. there are fewer 18–24s than we would typically like, but this does make sense and we would not expect many of this group to be responsible for their household's bills (See the Supplementary Information 2 [SI.2] for a detailed explanation on representativeness and comparison figures).

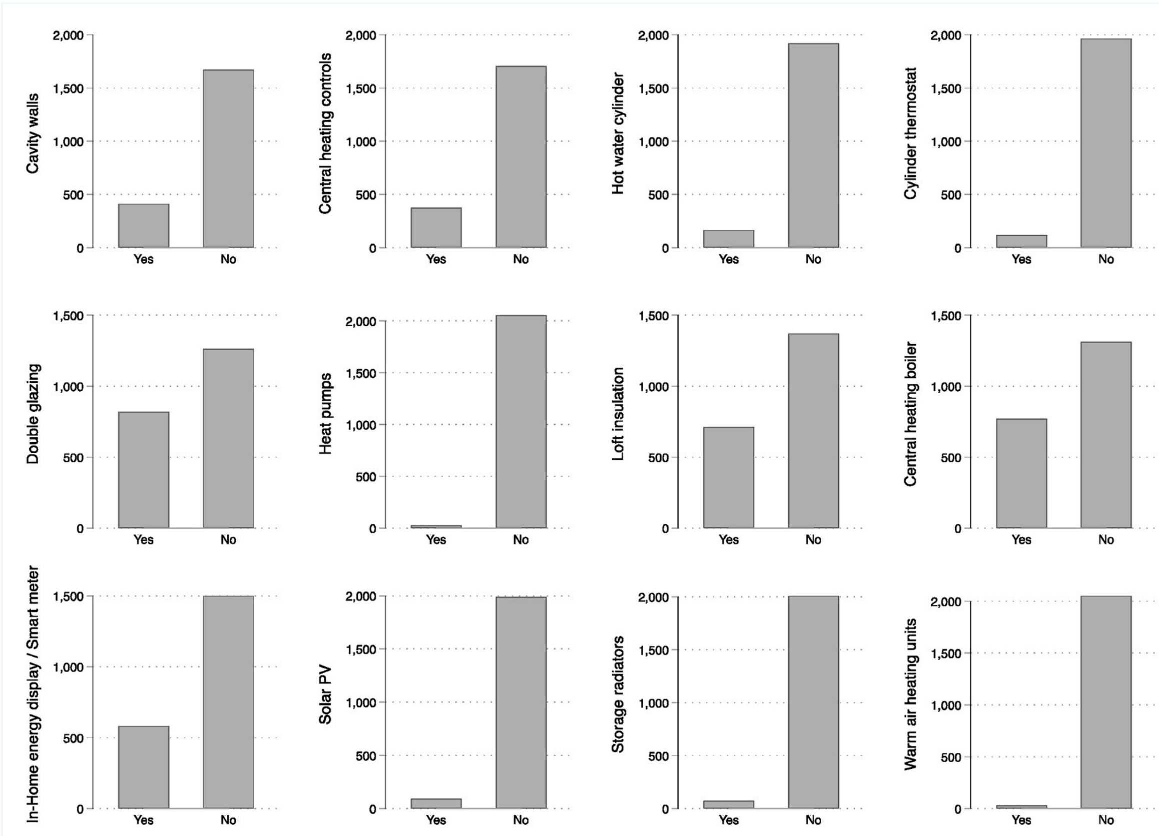

Fig. 1. Adoption of EE measures by type of measure across the sample
Note: The y-axis shows the number of respondents in the survey that reports having adopted the particular energy efficiency measure included in the graph.
Source: Own elaboration.

was selected to facilitate the comparison with future studies and based on the English Housing Survey. They are:

Low-cost EE measures.

1. Installation of loft insulation or extra loft insulation.
2. Installation of cavity wall insulation
3. Installation or upgrade of a hot water cylinder.
4. Installation of an in-home energy display or smart meter

High-cost EE measures.

1. Installation or upgrade of a hot water cylinder thermostat
2. Upgrade of central heating controls e.g. put new thermostatic radiator valve, replace central heating thermostat, replace central heating time clock/programmer.
3. Upgrade or replace existing storage radiators
4. Upgrade or replace a central heating boiler,
5. Upgrade or replace warm-air heating units,
6. Installation of a Solar PV system,
7. Installation of a manual feed biomass boiler e.g. pellets
8. Installation of an electric heat pump,
9. Energy efficient window systems, double or triple glazing.
10. Other.

Among the EE measures considered, double glazing systems were the EE measures more widely installed with approximately 40% of the households in the sample (820 over 2084) reporting to have installed those systems since they moved to their current address. It is interesting to see that, in relation to in-home energy displays and smart meters, only 30% of households declare the installation of a device of these characteristics (See Fig. 1). While it is possible that some dwellings were already equipped with a smart meter, around 70% of the households in the sample reported to have been living in their current address for more than 5 years (see Table A1 in the SI). Then we would expect a higher number of installations of this type of devices. In this regard, policy may not be creating the proper incentives for the adoption of such devices. Indeed, the UK's Smart Meter Implementation Program, projected that every household and small businesses across Great Britain would have installed a smart meter by 2020. However, only 7.14% of the target number had been installed by late 2016, and the last figures in 2022 shows that 55% of the meters in the residential sector are smart (UK Government, 2023). This may make difficult for the projected savings to be realized (Sovacool et al., 2017).

Regarding thermal insulation i.e. loft insulation and cavity walls; 34% of households (713) have installed loft insulation while only 20% (411) have installed some kind of cavity wall insulation. While the installation of a new traditional central heating boiler may not be considered by many as a measure that leads towards gaining in energy savings, the replacement of an old gas boiler with one of the highest standards, might deliver still some energy savings (DBEIS, 2023). In our sample 37% of the sample (771 households) have performed this kind of EE measure. For the rest of EE measure adopted, we find percentages of adoption below 18% (See Fig. 1). A figure with the percentage of households adopting the most relevant EE measures for energy efficiency and sustainability by time can be found in the SI.1 (SI.1 Fig. A2). This graph also shows the timing for different support schemes implemented by the UK Government. A table with additional descriptives about the variables in Figs. 1 and 3 can be found in the SI.1 (See Table A2)

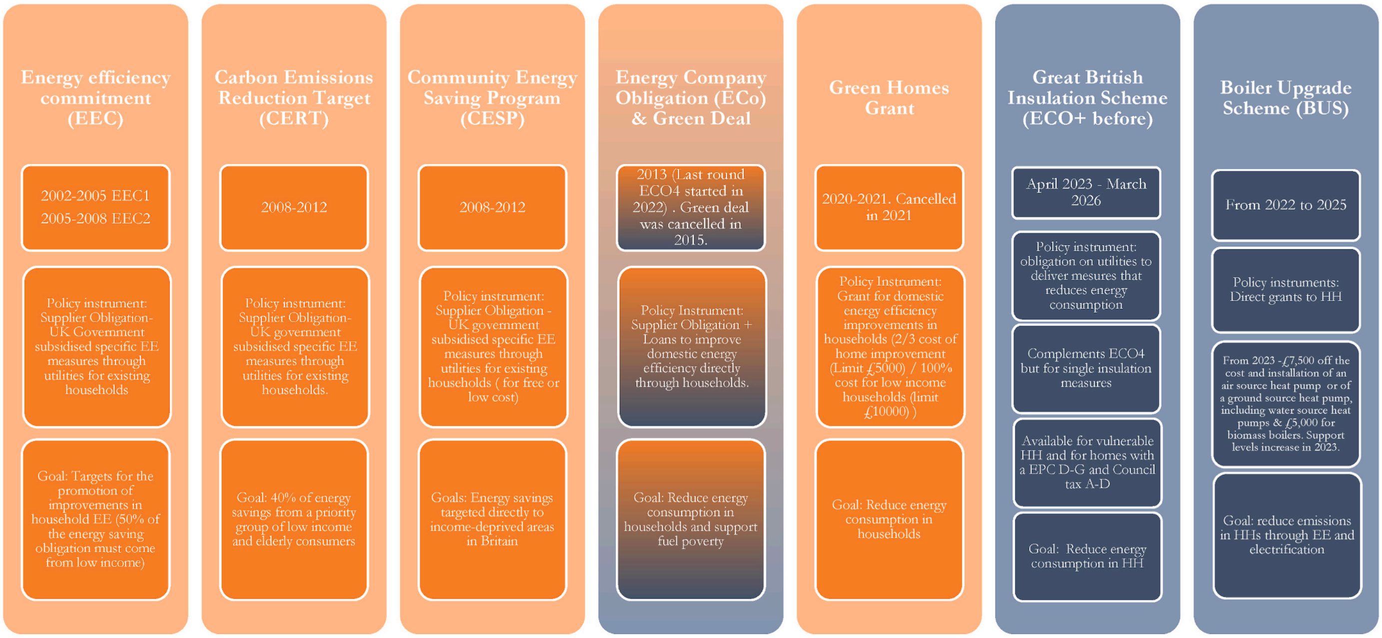

Fig. 2. Timeline of main residential building EE policies in the UK between 2002-2023[5]
Source: Updated from Peñasco and Anadón (2023) with information from OFGEM. In orange, we find the schemes that finished or have been cancelled. In blue, we find active schemes as per 2023.

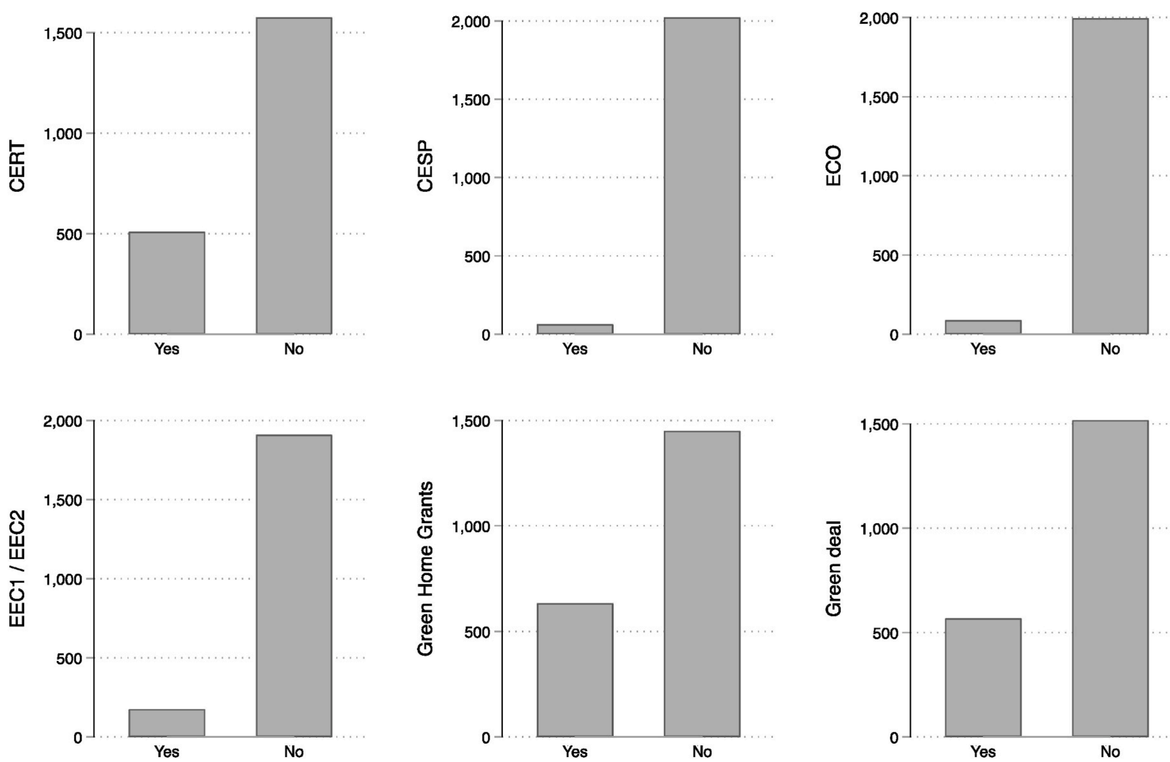

Fig. 3. Number of respondents aware of each of the programmes implemented at the national-level by the UK Government from 2002 to 2021
Note: The y-axis shows the number of respondents in the survey that reports having adopted the particular energy efficiency measure included in the graph. The figure does not include the last two schemes established by the UK government given that they were implemented after the collection of information from the survey.
Source: Own elaboration

3.1.2. Independent variables: Policy instruments and support schemes preferences

Understanding the preferences and circumstances under which households would adopt EE measures is essential to design effectively and efficiently the policy and support programmes that accelerate the deployment of such technologies and measures at the needed pace. To understand better those policy preferences, the survey included questions related to how likely a household would be to adopt an EE measure under a particular set of circumstances that mirrors the types of policy instruments available to governments to promote faster adoption. For

Table 2
Category of policy preferences.

Type of policy instrument	Sub-category
Regulatory instruments	Government adoption of higher building EE standards Government strict implementation of existing building EE standards
Economic and Financial Instruments	Government implementation of tax incentives and/or tax credits to promote the adoption of EEMs; Government financing the adoption of EE measures through **loans** to be repaid. Government financing the adoption of EE measures through **grants** Government financing utility companies to install EE measures in households
Soft instruments	Government reduction of administrative procedures to apply for support to install EE measures Government provision of more information about the efficient use of energy Government provision of more information about the potential savings that can be derived from the adoption of EE measures Government provision of more information on the programmes/schemes available to finance the EE measures.

Note: We have used an 11 point Likert scale to measure the policy preferences of respondents. In particular, we chose that instead of other traditional Likert Scales (5-point or 7-point) as an 11-Point Likert Scale offers a better precision and the highest level of granularity, allowing respondents to express more finely tuned attitudes. It also enhances the sensitivity of data, making it easier to detect small differences or changes over time (or between regions like in this case). An 11-point liker scale is also richer and useful for research that requires detailed feedback or when measuring constructs with high variability.

the purpose of this paper, we have asked questions related to three types of instruments i.e. regulation, economic and financial instruments, and soft instruments in the form of information.

To provide some context, the UK has implemented a series of national-level energy efficiency programmes during the last two decades. These policies have evolved to address the growing need for energy efficiency (and sufficiency) in households in the UK. Key programs include the Energy Efficiency Commitment (EEC) (2002–2008), the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (2008–2012), the Green Deal (2013–2015), the Energy Company Obligation (ECO) scheme, running in various phases since 2013; or the Green Home Grants (2020–2021). More recently, the UK Government has implemented the Great British Insulation Scheme (2023–2026) and the Boiler Upgrade Scheme (BUS) (2022–2025) (see Fig. 2 for further details).

Given the lack of awareness detected in respondents e.g. only half of the sample were aware of at least one of the supporting schemes of the UK along time (See Fig. 3), focusing on soft instruments like the provision of information seems essential in order to boost EE measure adoption.

To test the probability of adoption of EE measures subjected to the implementation of different policy instruments we use (see Table 2):

Yet, beyond policy variables, it is essential for policymakers to consider the socio-demographic and predictors of residential energy consumption when designing energy efficiency policies for heating, to ensure that these policies effectively target the specific needs and behaviours of households (Frederiks et al., 2015). Analyzing the behaviors related to technology acquisition and use among UK households, including the patterns of cleaner technologies ownership and uptake, is vital for assessing the effectiveness of government policies aimed at encouraging energy-saving measures (Spyridaki et al., 2020; UK Green Building Council, 2021). In this sense, factors that affect the uptake of EE measures in UK homes include the type of housing, the socio-economic status of the residents, their attitudes and awareness regarding energy use and costs, among other contextual elements (see Boardman, 2015; Rosenow and Eyre, 2016 among others) (See below).

Table 3
Baseline estimations – probability of adoption of EE measures (Marginal effects).

	(1)	(2)	(3)
Dep: Adopted EE measures	Logit	Cloglog	Poisson
Tax credits	0.00543	0.00566	0.0506*
	(0.00758)	(0.00659)	(0.0308)
Loans	−0.00968**	−0.00915**	−0.0484**
	(0.00489)	(0.00463)	(0.0204)
Grants	0.0113**	0.0118**	0.0403
	(0.00560)	(0.00576)	(0.0301)
Release admin. barriers	0.0167*	0.0156**	0.0181
	(0.00880)	(0.00775)	(0.0369)
Utilities involvement	−0.00931	−0.00708	−0.0181
	(0.00572)	(0.00521)	(0.0233)
Info. Efficient use	−0.0181*	−0.0214**	−0.0399
	(0.00936)	(0.00864)	(0.0373)
Info. potential savings	0.0204**	0.0217**	0.0698*
	(0.0102)	(0.00897)	(0.0408)
Info. Support schemes	−0.0113	−0.00922	−0.0201
	(0.0101)	(0.00905)	(0.0382)
Higher EE. standards	0.0128	0.0102	0.0294
	(0.00901)	(0.00814)	(0.0342)
Stronger EE. standards	−0.00196	0.00124	0.0133
	(0.00925)	(0.00848)	(0.0345)
Awareness schemes	0.0207**	0.0171*	0.137***
	(0.00983)	(0.00911)	(0.0389)
Tenure (b. Owner)			
Renter	−0.195***	−0.193***	−0.820***
	(0.0381)	(0.0362)	(0.133)
Other	−0.229*	−0.199*	−1.006***
	(0.120)	(0.117)	(0.337)
Living period (b.≤1 month)			
>1 month &≤6 months	0.308*	0.282	1.097**
	(0.172)	(0.184)	(0.531)
>6 months &≤12 months	0.0671	0.0588	0.0739
	(0.167)	(0.181)	(0.433)
>1 year &≤2 years	0.114	0.0936	0.255
	(0.163)	(0.176)	(0.434)
>2 years &≤5 years	0.271*	0.255	0.696*
	(0.156)	(0.169)	(0.414)
>5 years &≤10 years	0.380**	0.352**	0.991**
	(0.154)	(0.167)	(0.405)
>10 years	0.451***	0.431***	1.791***
	(0.152)	(0.166)	(0.397)
Dwelling characteristics controls	Included	Included	Included
EPC rating control	Included	Included	Included
Control regions	Included	Included	Included
N	1369	1369	1369
pseudo R^2	0.209	0.2107	0.100
AIC	1405.0	1402.8	4876.8
BIC	1681.8	1679.6	5153.6

Note: Standard errors in parentheses * $p < .10$, ** $p < .05$, *** $p < .01$
Additional dwelling characteristics controls include: type of dwelling, year of construction, surface (sqf), number of bedrooms, HH size, old members living in the households, young members living in the households and income.

3.1.3. Other explanatory and control variables

The selection of the explanatory variables was based on relevant literature, findings and insights from previous studies in the field (See

[5] In addition to the schemes shown in Fig. 1, the UK Government set up non-EE focused heating and housing benefits that may influence both the energy consumption and expenditure of households. For example, we find the Warm Home discount scheme that was established by the Warm Home discount regulation in April 2011. Its main aim is to fight fuel poverty in Britain. Under this scheme, households on risk of fuel poverty are allowed to receive an electricity bill rebate of £150 year. This programme is expected to be active until 2026.

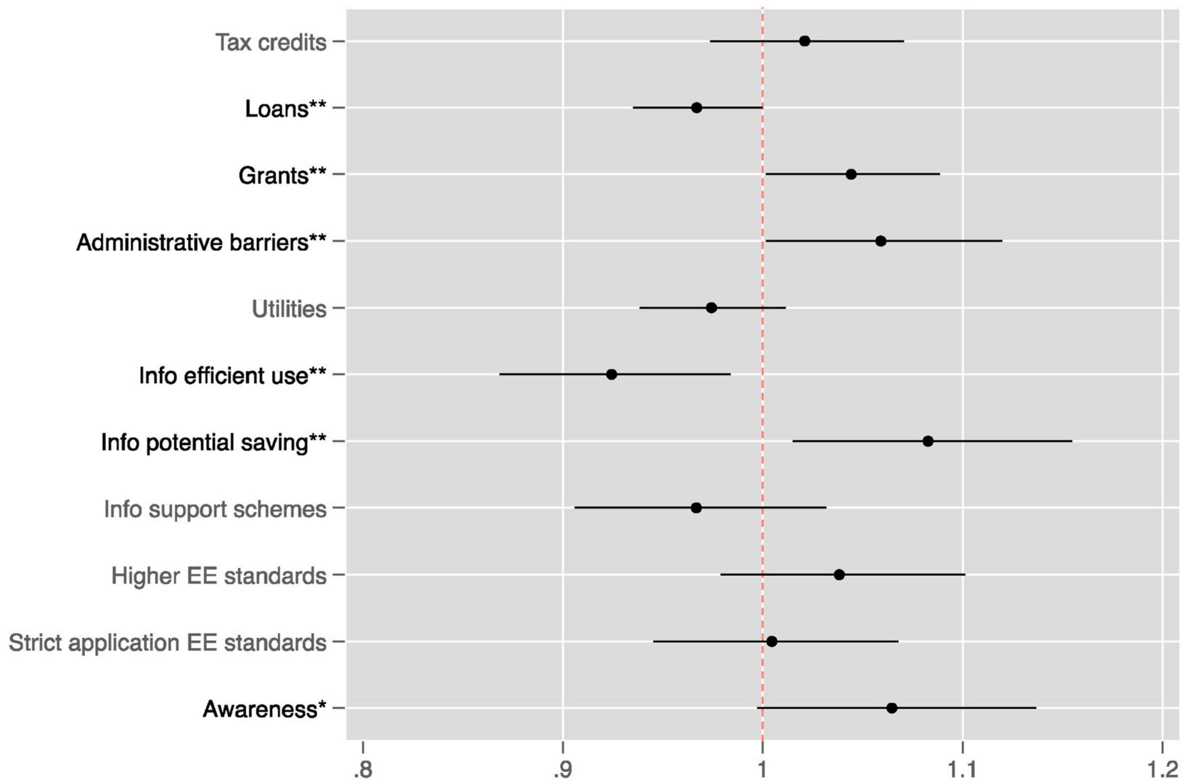

Fig. 4. Odds-ratio for policy drivers in the baseline estimations
Note: The variables in bold are statistically significant and the stars show the level of significance in the baseline estimation (Column 3) (*p < .10, **p < .05, ***p < .01)

Section 2). This research groups drivers/factors behind the adoption of EE measures in three different categories. Following Spyridaki et al. (2020) for the case of Greece, our groups are divided in: i. Dwelling characteristics, ii. Socio-economic characteristics/demographics of households, iii. Households' preferences in regards to policies that could promote the adoption of EE measures.

A. Dwelling characteristics

Dwelling characteristics were collected together with the questions related to the adoption of different EE measures. Characteristics include the tenure status, i.e. if the occupants are owners, renters or if they live rent free in the property of somebody else, usually family and/or friends; the type of dwelling e.g. detached/semi-detached or apartment; the age of the dwelling, i.e. the year of construction of the dwelling in categories; the surface habitable in squared-feet (sqf) and the Government Office Regions (GOR) in which the household is located in[6] (See Table 1 of descriptives above and SI.1 Table A1 for a detailed explanation of the measurement of the variables).

The majority of the respondents (~70%) own their residence. The remaining 30% either rent their dwelling (~27%) or live with any other type of tenure agreement (~3%). Interestingly, the majority of respondents live in dwellings constructed between 1930 and 1999 (~67%), while ~20% live in dwellings constructed before 1930. Only around ~16% of respondents live in dwellings constructed after 2000 (only 8% after 2010). This data is relevant given that only the latter category would comply with the current and more up to date building codes in the UK (See HM Government, 2020).[7] Regarding the type of dwelling, while highly correlated with the surface and the number of bedrooms, the majority of respondents live in semi-detached houses (~29% of the sample), followed by detached and terraced houses (representing around ~22% of the sample respectively). Apartments make approximately 15% of the sample and the remaining includes maisonettes, bungalows and other types of dwellings (~11%). The majority of dwellings count with 3 bedrooms (~41%) followed by 2- and 4-bedroom dwellings (~28% and 17% respectively)[8] Households are distributed across the British geography with a slight concentration in the South East (~15% of respondents). The other regions vary between ~4% of the sample (North East) to ~ 11% of the sample (North West).

B. Socio-demographic characteristics of occupants

As part of the survey we asked questions related to the socio-demographic profile of the households and their occupants e.g. the number of members living in the household and the gross monthly income of both, the respondent but importantly, the household as an entity. Information has been collected as well in relation to the number of people younger than 16 and older than 75 living in the household. The average respondent is 52 years old and is the breadwinner in a household that is formed by an average of 2.3 members (~90% of the sample includes households of no more than 4 members). Around 32% of

[6] Households in Northern Ireland were not included in the sample.
[7] A timeline of the key energy building regulations in the UK can be found in the SI.1 (Box A2).

[8] While there is information in the survey about the surface of the dwelling in squared meters, the variable is less complete than the number of bedrooms with more than 50% of the sample reporting they do not know the squared feet of their dwellings. If several respondents are foreign to the British system, this high number of 'don't know' responses could be due to a lack of knowledge about the equivalences between the metric system and the Imperial System of measurements. As such we will also use the number of bedrooms as a proxy for the surface of the household.

Table 4
Segmentation estimations – probability of adoption by type of measure.

	(1)	(2)	(3)	(4)
	Low-cost measures	High-cost measures	Low-cost measures	High-cost measures
Dep: Adopted EE measure	Cloglog	Cloglog	Logit	Logit
Tax credits	0.00616	0.0109	0.00565	0.00882
	(0.00722)	(0.00706)	(0.00787)	(0.00788)
Loans	−0.0126**	−0.00637	−0.0126**	−0.00545
	(0.00549)	(0.00516)	(0.00563)	(0.00537)
Grants	0.0176**	0.00157	0.0186***	0.00313
	(0.00724)	(0.00687)	(0.00716)	(0.00637)
Release admin. barriers	0.00474	0.0157*	0.00443	0.0150*
	(0.00949)	(0.00837)	(0.0100)	(0.00912)
Utilities involvement	−0.00613	−0.00291	−0.00802	−0.00407
	(0.00626)	(0.00574)	(0.00665)	(0.00592)
Info. Efficient use	−0.00908	−0.0216**	−0.00880	−0.0197**
	(0.0101)	(0.00913)	(0.0106)	(0.00957)
Info. potential savings	0.0238**	0.0141	0.0231**	0.0151
	(0.0106)	(0.00970)	(0.0110)	(0.0102)
Info. Support schemes	−0.0181*	0.00197	−0.0185*	0.00172
	(0.00982)	(0.00990)	(0.00994)	(0.0113)
Higher EE. standards	0.0106	0.0116	0.0126	0.0128
	(0.00931)	(0.00873)	(0.00912)	(0.00971)
Stronger EE. standards	0.0111	−0.00753	0.00927	−0.0113
	(0.00983)	(0.00897)	(0.00983)	(0.00984)
Awareness schemes	0.0177	0.0211**	0.0226**	0.0257**
	(0.0109)	(0.0100)	(0.0111)	(0.0108)
Tenure (b. Owner)				
Renter	−0.210***	−0.148***	−0.214***	−0.143***
	(0.0383)	(0.0377)	(0.0385)	(0.0383)
Other	−0.0842	−0.282**	−0.103	−0.284**
	(0.126)	(0.132)	(0.124)	(0.131)
Living period (b.≤1 month)				
>1 month &≤6 months	0.101	0.345*	0.137	0.367**
	(0.197)	(0.190)	(0.182)	(0.169)
>6 months &≤12 months	−0.134	0.112	−0.118	0.121
	(0.189)	(0.180)	(0.172)	(0.156)
>1 year &≤2 years	−0.0623	0.181	−0.0313	0.192
	(0.189)	(0.179)	(0.172)	(0.156)
>2 years &≤5 years	0.0668	0.250	0.0977	0.253*
	(0.183)	(0.172)	(0.166)	(0.148)
>5 years &≤10 years	0.141	0.378**	0.168	0.397***
	(0.181)	(0.170)	(0.164)	(0.147)
>10 years	0.246	0.494***	0.272*	0.503***
	(0.179)	(0.169)	(0.162)	(0.145)
Dwelling characteristics controls	Included	Included	Included	Included
EPC rating control	Included	Included	Included	Included
Region control	Included	Included	Included	Included
N	1369	1369	1369	1369
pseudo R^2	0.1592	0.1930	0.160	0.192
AIC	1679.3	1576.1	1677.8	1577.9
BIC	1956.1	1852.8	1954.5	1854.6

Note: Standard errors in parentheses* p < .10, **p < .05, ***p < .01. Additional dwelling characteristics controls include: type of dwelling, year of construction, surface (sqf), number of bedrooms, HH size, old members living in the households, young members living in the households and income

households include a minor while only 11% report living with at least an elderly member. The average gross income of the household is in the band between £30,000 to £34,999 per year. As aforementioned around 50% of the sample has been living in the same household for the last 10 years (See Table 1 of descriptives and SI.1 for a detailed explanation of the measurement of the variables).

C. Dwellings' energy and environmental profile

One of the main particularities of the UK energy consumption and demand in the residential sector is the important percentage of households that still use gas as their main source of heating. On average around 74% of households still use gas central heating as their main heating source (Stewart, 2023). Our sample also shows this pattern and 83% of the households in the sample uses gas as the main source of heating. The survey data shows a huge lack of knowledge about the Energy Performance Certificate band in which households are subscribed. More than 60% of the households in the sample report not knowing their EPC band. Out of those reporting a particular EPC rating, around 25% belongs to the categories C and D. Only 70% of the sampled households reported knowing their average gas bill in kWh. This, together with the lack of awareness about particular support schemes shown above, is already substantive evidence that support the lack of knowledge in regards to energy affairs in the residential sector.

3.2. Methods

As mentioned in the introduction, this research aims at analysing the probability of households to have adopted an EE measure. The main goal is to estimate the potential effect of policies such as tax incentives, rebates, and/or information campaigns on household adoption, while controlling for household characteristics such as size, construction year, income and other socio-demographic covariates. For that purpose, discrete choice econometric techniques are used. For each possible EE measure installed in the household after the respondents moved in, we calculate the probability of each household *i* to have installed any of the EE measures included in the survey.

The dichotomous logit model is summarized in (1):

$$P(y_i = 1|X_i) = \bigwedge(\beta.X_i) = \frac{e^{\beta.X_i}}{1 + e^{\beta.X_i}} \tag{1}$$

Where y_i is the dependent variable describing if a household *i* has adopted an EE measure or not; x_i is the vector of independent/explanatory variables for the *i*th household, β is the parameter vector to be estimated; and Λ is the logistic distribution.

Given the binary nature of our dependent variable, we have estimated a model that caters to its asymmetrical distribution (Collet, 2003). In addition to the conventional logit model, a complementary log-log (Cloglog) model is also employed. The Cloglog model is particularly suitable at handling binary outcomes within skewed datasets and expands upon the traditional logit model. It calculates the probability of an occurrence i.e., a household adopting an EE measure, by taking the complement of the logarithm of the chance of the event not happening. Furthermore, the Cloglog model introduces a dispersion parameter that accommodates over-dispersion in the dataset.[9]

$$Prob\ (Y_i = 1|Z_i^*) = e^{\left(-e^{\left[\alpha+\beta^* Z_i^*\right]}\right)} \tag{2}$$

The discrete choice econometric methods, specifically the logit and complementary log-log used in this paper are useful in addressing the three hypotheses proposed in the previous section regarding energy efficiency (EE) measures adoption in households. The logit model is used to estimate the probability of households adopting EE measures based on public policies such as tax incentives, rebates, and information campaigns, while controlling for household characteristics. This approach directly addresses Hypothesis 1 by quantifying the potential impact of these policies on adoption probabilities. Alongside the logit

[9] Dendramis et al. (2020) claimed that the cloglog distribution is constrained to exhibit left-skewness, thereby limiting its capacity to accurately model the underlying data distribution. To mitigate this limitation, they proposed the use of a binary link function that is more flexible than the cloglog. This approach builds upon the skewed logit distribution initially introduced by Nagler (1994). Given the distribution of our dependent variable, the Cloglog estimation and the skewed logit shows the same results. We include in this paper the Cloglog. The Stata results from the skewed logit are available upon request.

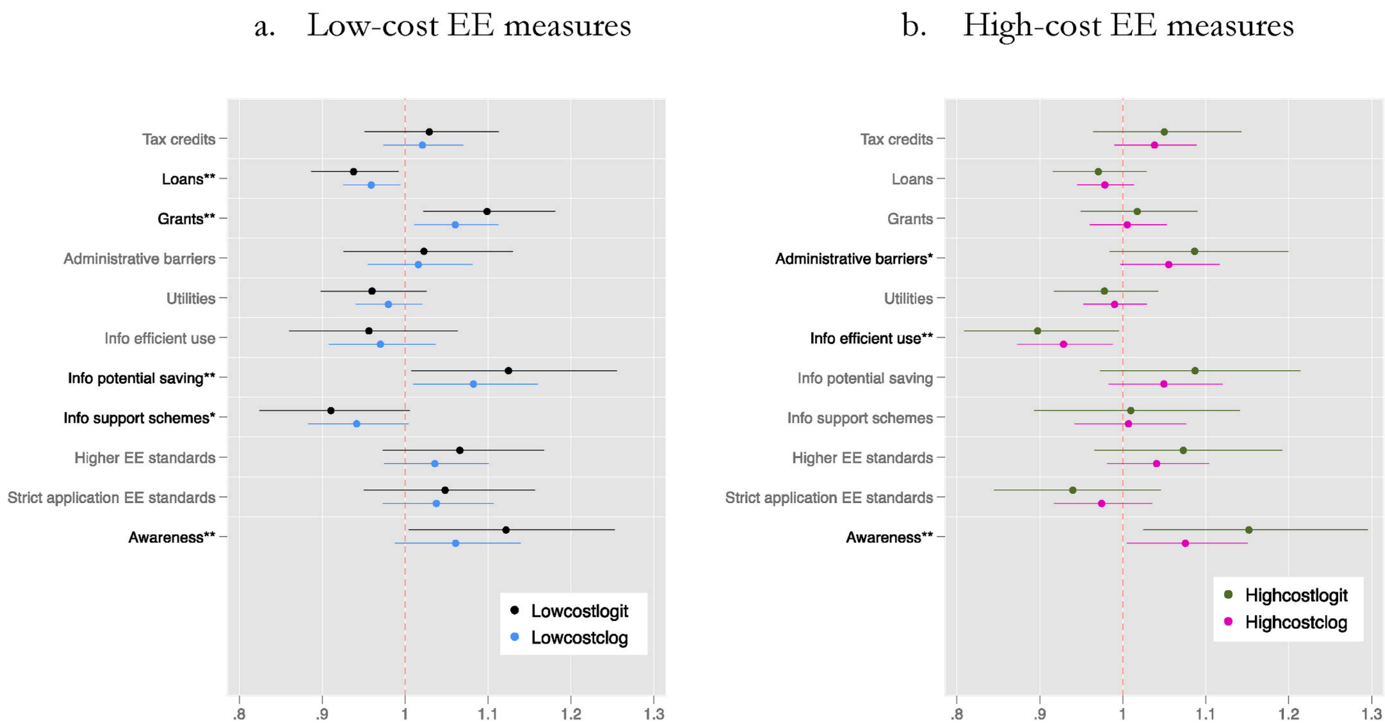

Fig. 5. Odds-ratio for policy drivers per type of measures (Panel a. Low-cost vs. Panel b. High-cost)
Note: The variables in bold are statistically significant and the stars show the level of significance derive from Table 4 (Columns 1–3 and 2–4) (*p < .10, **p < .05, ***p < .01)

model, the Cloglog model is employed across all hypotheses to complement the analysis. This dual-model approach allows for a more comprehensive understanding of the factors influencing EE adoption by addressing any limitations inherent in a single model approach. For Hypothesis 2, both models are used to evaluate the relative effectiveness of policies that tackle informational and administrative barriers compared to other types of interventions, testing if soft policies can facilitate higher adoption rates. Finally, for Hypothesis 3, the inclusion of multiple explanatory variables and interaction terms in both models enables a holistic examination of how various barriers and motivators interact to influence household decisions. The robust parameter estimation and statistical tests from these models provide valuable insights into designing effective, multifaceted energy policies.

All regression parameter estimates are evaluated using standard errors robust for heteroskedastic error terms and misspecifications. Weighting is used to adjust for oversampling of certain groups or to account for the probability of selection of individuals within the sample. For further elaboration on the weighting used in this analysis see SI. 2.

4. Results

4.1. Baseline estimations

Our econometric results reveal nuanced insights into the policy drivers to foster the adoption of energy efficiency (EE) measures. Our quantitative analysis identifies social challenges such as lack of information or the lack of incentives as significant barriers to adoption. Soft instruments (e.g., information dissemination) and financial support mechanisms (grants) emerge as critical factors, affirming their foundational role in overcoming barriers to EE adoption. This finding is consistent with existing literature that highlights the effectiveness of such interventions in promoting the adoption of energy efficiency measures (Gillingham and Palmer, 2014; Allcott and Mullainathan, 2010).

The paper has analysed in particular the role of consumers' policy preferences to foster the adoption of particular EE measures. These policies are divided in Regulatory instruments e.g. building codes and/or energy efficiency standards, and renewable energy obligations for utilities; economic, financial or fiscal instruments e.g. grants, loans and/or tax credits; and soft instruments like e.g. the reduction of administrative barriers for the application to support schemes, and different types of information. Overall, significant barriers to the adoption of EE measures include lack of information, financial constraints, and perceived administrative difficulties associated to the application for particular programmes.

Table 3 includes logit and cloglog estimations to calculate the probability of adoption of an EE measure (any) (columns 1 and 2), and a Poisson regression with a count variable considering the number of EE measures adopted by a particular household (column 3) in marginal effects. In regards to economic, financial and fiscal instruments, the provision of loans that need to be returned by households does not appear to be an attractive tool for dwellings to foster the adoption of EE measures. This variable, indeed, is statistically significant but negative with marginal effects on the rage of [−0.048, −0.0092]. Therefore, there is a preference by UK households towards instruments that do not imply any return. Yet, the majority of instruments established by the UK government to promote the adoption of EE measures have taken the form of mostly grants and/or partial grants together with energy efficiency obligations i.e. the involvement of utilities. Interestingly, our results find that fiscal incentives in the form of tax credits may be important among those installing several measures at home. We would expect that those installing several measures and/or doing deep energy efficiency renovations at home have the available budget for considering the disbursement of the upfront investments needed to fully retrofit their dwellings. Tax credits for installing energy efficiency measures are particularly appealing to wealthier individuals. These tax credits can substantially lower the cost of energy-efficient upgrades, making them financially attractive for homeowners who can afford the initial investment in technologies like solar panels, heat pumps, and energy-efficient appliances (Gillingham et al., 2009; Gago et al., 2013).

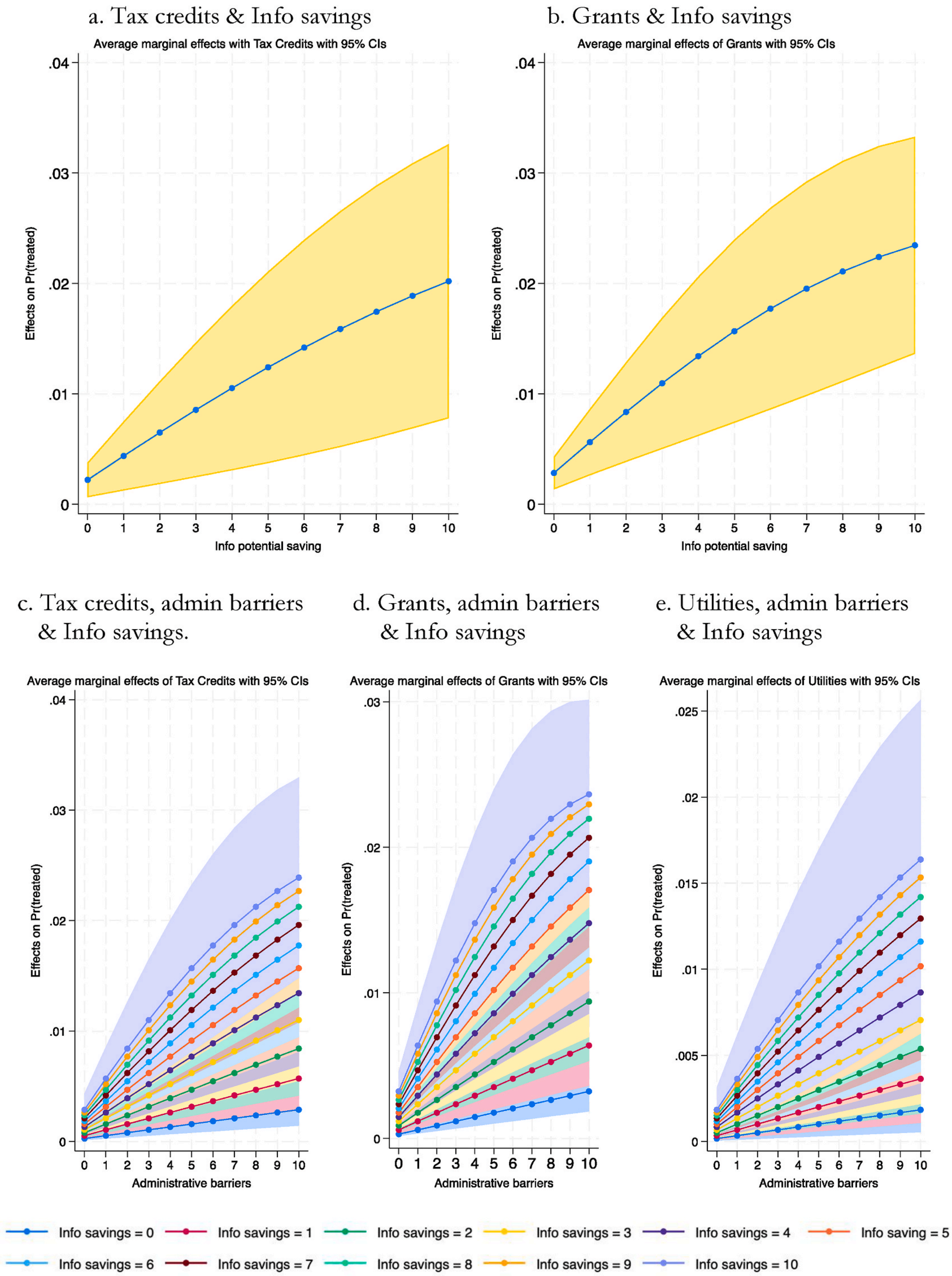

Fig. 6. Average marginal effects (AME) of policy combinations – adoption of EE measures

Note: Top left: The blue line represents the effects on the probability of adopting an energy efficiency measure when governments implement tax credits jointly with the provision of information about savings (x-axis) (95th % CIs in yellow). Top right: The blue line represents the effects on the probability of adopting an energy efficiency measure when governments implement grants jointly with the provision of information about savings (x-axis) (95th % CIs in yellow). Bottom left: The colour lines from blue (bottom) to purple (up) represent the effects on the probability of adopting an energy efficiency measure when government implement tax credits jointly with the easing of administrativ6e barriers (x-axis) and with the scale of preferences by households in regards to information about savings (colour lines) from 0 (blue bottom – very unlikely to adopt an energy efficiency measure if the government put in place policies based on information about the potential savings of the particular energy efficiency measures) to 10 (purple up – very likely to adopt an energy efficiency measure if the government put in place policies based on information about the potential savings of the particular energy efficiency). The bottom centered graph and the bottom right graph present the same information than the bottom left graph but for grants and the involvement of utilities together with the easing of administrative barriers (x-axes) and the provision of information (colour lines from 0 to 10) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Source: own elaboration

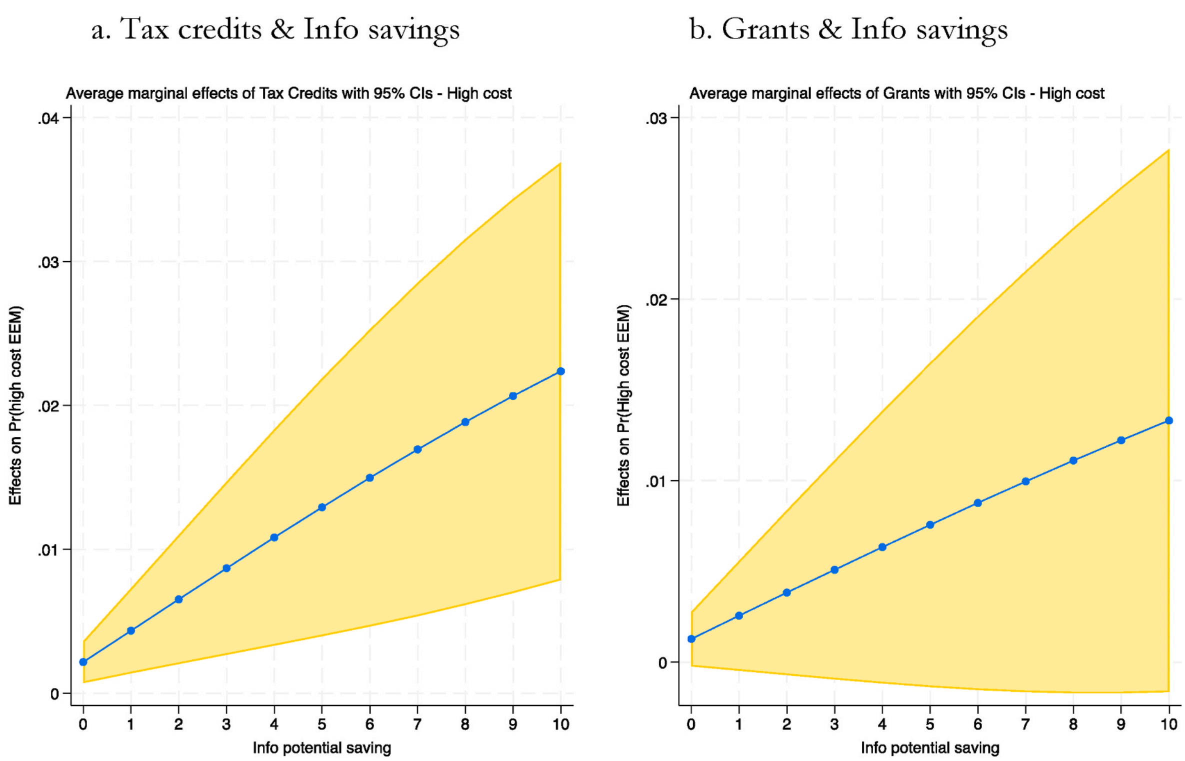

Fig. 7. Average marginal effects of policy combinations (one + one) – adoption of high-cost EE measures
Note: Left panel: The blue line represents the effects on the probability of adopting a high-cost energy efficiency measure when governments implement tax credits jointly with the provision of information about savings (x-axis) (95th % CIs in yellow). Right panel: The blue line represents the effects on the probability of adopting a high-cost energy efficiency measure when governments implement grants jointly with the provision of information about savings (x-axis) (95th % CIs in yellow). Source: Own elaboration

However, it is important to note that tax credits may not benefit everyone equally. Studies have indicated that non-refundable tax credits are inequitable, as they are useful only for individuals who incur a certain level of tax liability, potentially excluding lower-income individuals from fully benefiting from such incentives and benefiting wealthier families (Spence et al., 2012).

Grants on the contrary seems to be one of the preferred policy instruments by households. The probability of adopting an EE measure would increase by around 1% if the UK government had as a policy preference the provision of grants to foster the adoption of EE measures in the residential sector. This has been one of the main policy instruments implemented by the British Government during the last years and, all in all, results have not been as expected initially. This outcome led to the cancellation of some support schemes as for example the Green Deal and/or the Green Home Grants due to a lack of applications. Our results show that releasing administrative barriers for the application to support schemes are statistically significant with marginal effects on the range of [0.016,0.017]. To the best of our knowledge, this result has not been explored previously by the literature and it seems of special importance in the context of the UK. As mentioned above, e.g. The Green Homes Grant designed to subsidize the cost of energy-efficient home improvements in England, was closed to new applications at the end of March 2021. Initially announced in July 2020, it intended to run until March 2022, and it was designed to cover a significant portion of the costs for eligible energy efficiency improvements in households. Despite its promising goals, the scheme was terminated earlier than planned due to possible 'failures' in implementation. The scheme opened during one of the highest COVID peaks in England and in the Autumn-Winter seasons which elevates the organisational efforts of households. Also, to apply to the scheme, the owners and/or residents had to, first, get a quote from a TrustMark or MCS accredited installer that has approved the work for the particular property. It was recommended to get at least three quotes. Once the quote was received, the households could apply for the voucher on the government's website providing information about the owner of the property, the people living in the property, the quote and the TrustMark license number of the installer. The administrative procedure may have been one of the causes why residents may have found difficult to apply and therefore one of the reasons for the cancellation of the support scheme. Our results seem to support this hypothesis and easing the administrative procedures may be an important step in the implementation of future support schemes.

In regard to soft instruments, the provision of information about how to efficiently use devices do not seem to play a role in increasing the probability of adoption EE improvements. However, the provision of information about the potential savings to be achieved after the installation of EE measures appears to be one of the most relevant factors for promoting the adoption of such measures with marginal effects on the range of [0.020, 0.070]. These results may not be surprising if we consider that the information about the efficient use of devices does not have as a direct target the installation of new measures or EE improvements but mainly the learning processes in the use of those already owned by households. The provision of information about potential energy savings and, therefore, economic benefits after the installation of a measure seems to have a more direct impact on the probability of adoption in the UK. Importantly, having an extensive knowledge about several available schemes increases greatly the probability of adopting EE improvements with marginal effects around [0.017, 0.137].

While additional control variables in relation to dwellings' characteristics have been included[10] (See Stata codes for calculation), it is

[10] Type of dwelling, year of construction, surface (sqf), number of bedrooms, HH size, old members living in the households, young members living in the households, income, EPC rating

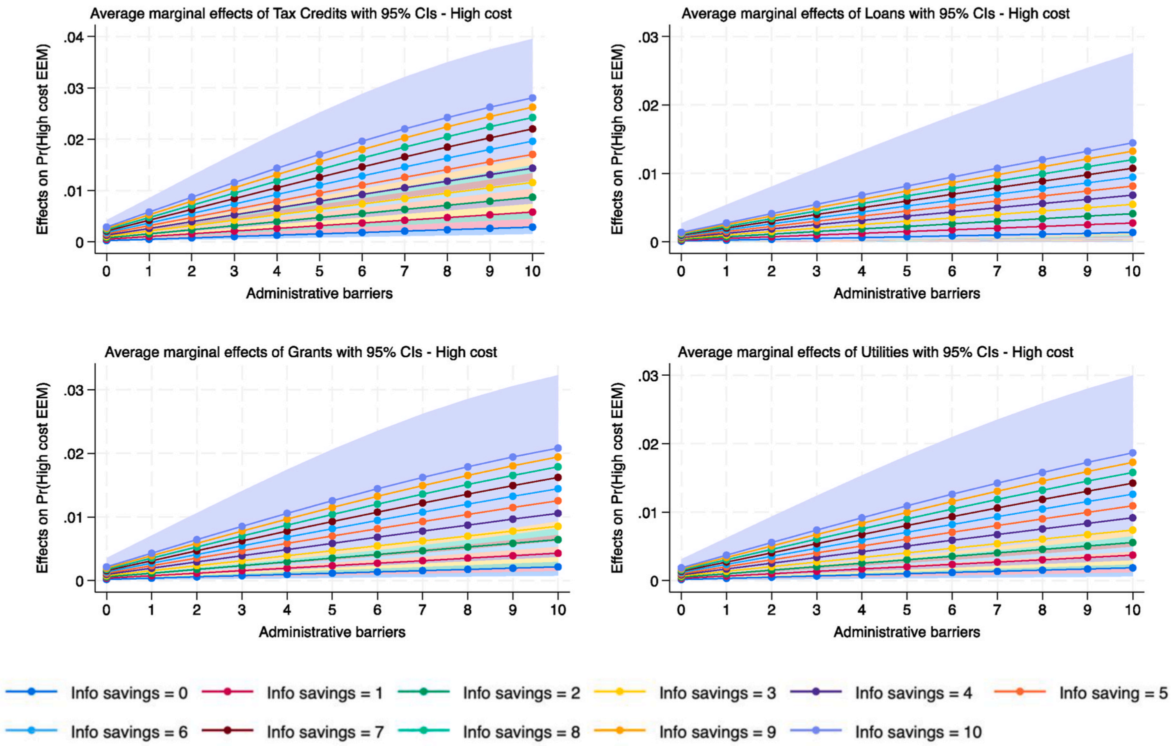

Fig. 8. Average marginal effects of policy combinations (>2) – adoption of high-cost EE measures
Note: Top left: The colour lines from blue (bottom) to purple (up) represent the effects on the probability of adopting a high cost energy efficiency measure when government implement tax credits jointly with the easing of administrative barriers (x-axis) and with the scale of preferences by households in regards to information about savings (colour lines) from 0 (blue bottom – very unlikely to adopt an energy efficiency measure if the government put in place policies based on information about the potential savings of the particular energy efficiency measures) to 10 (purple up – very likely to adopt an energy efficiency measure if the government put in place policies based on information about the potential savings of the particular energy efficiency). The top right, bottom left and bottom right graphs present the same information that the top left graph but for loans, grants and the involvement of utilities together with the easing of administrative barriers (x-axes) and the provision of information (colour lines from 0 to 10) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: own elaboration

worthy to highlight the results on the type of tenure and time living in the dwelling given the implications for the design of effective policies to foster the adoption of EE improvements. It is well known in the literature on energy efficiency in the residential building the dichotomy between renters and owners. The probability of adoption EE measures in residential buildings is statistically smaller when we talk about tenants. Policies therefore may need to target more directly this segment of the population given that in the UK, as of 2022, 35.7% of the population rented their dwellings, with the majority renting from a private landlord or being able to engage more effectively with the landlords of such properties given that tenants might not often engage in long-term planning due to the short-term nature of their tenancies (Hope and Booth, 2014). Importantly, it seems relevant, from a policy perspective, to target residents either at the moment of changing houses i.e. during the first year after they move into a new property; and or those who have been living in the same property for more than 5 years. Moving homes and the period of adaptation right after the change in properties, appears in the literature as one of the most common drivers associated with the adoption of energy efficiency heating measures (see Curtis and Grilli, 2021 for Ireland; Rinkinen and Jalas, 2016 for Finland). Our results seem to confirm this literature for the British case.

The role of other control variables, such as household size, characteristics of the members of the family and property characteristics, aligns with traditional expectations, indicating a consistent influence on the likelihood of adopting EE measures. This finding reinforces the value of incorporating comprehensive controls in modelling EE adoption behaviours (Brounen et al., 2013).

Fig. 4 shows graphically the size of the odd ratios for the policy variables included in the regression tables for our preferred model i.e. the cloglog, due to its slightly lower AIC.

The results in Table 3, and in line with literature, conclude that energy efficiency technical improvements in households are driven by a variety of policy drivers, confirming therefore our first hypothesis. Table A3 in the SI.1 shows the coefficients of the regression.

4.2. Segmentation of the sample by cost of EEMs

Our findings support a multifaceted policy approach that combines soft instruments and financial grants to catalyze EE adoption across households. Yet, while the adoption of energy efficiency measures in households is influenced by various policy drivers, the cost of the technology plays a significant role in shaping these drivers. Our results show that addressing administrative barriers more vigorously for high-cost measures can further unlock the potential for energy efficiency improvements (See Table 4 and Fig. 5). Our analysis further delineates the potential differences between the drivers of high-cost and low-cost EE measures, as defined by the English Housing Survey (EHS), revealing distinct adoption dynamics. High-cost measures face amplified barriers, including more pronounced administrative hurdles, underscoring the need for streamlined processes and enhanced support mechanisms (Wilson et al., 2015) (See Columns 2 and 4).

Differential impacts observed between high-cost and low-cost EE measures suggest nuanced policy implications. Specifically, while soft instruments and financial incentives broadly support EE adoption, the intensified administrative barriers associated with high-cost interventions necessitate targeted strategies to mitigate these obstacles

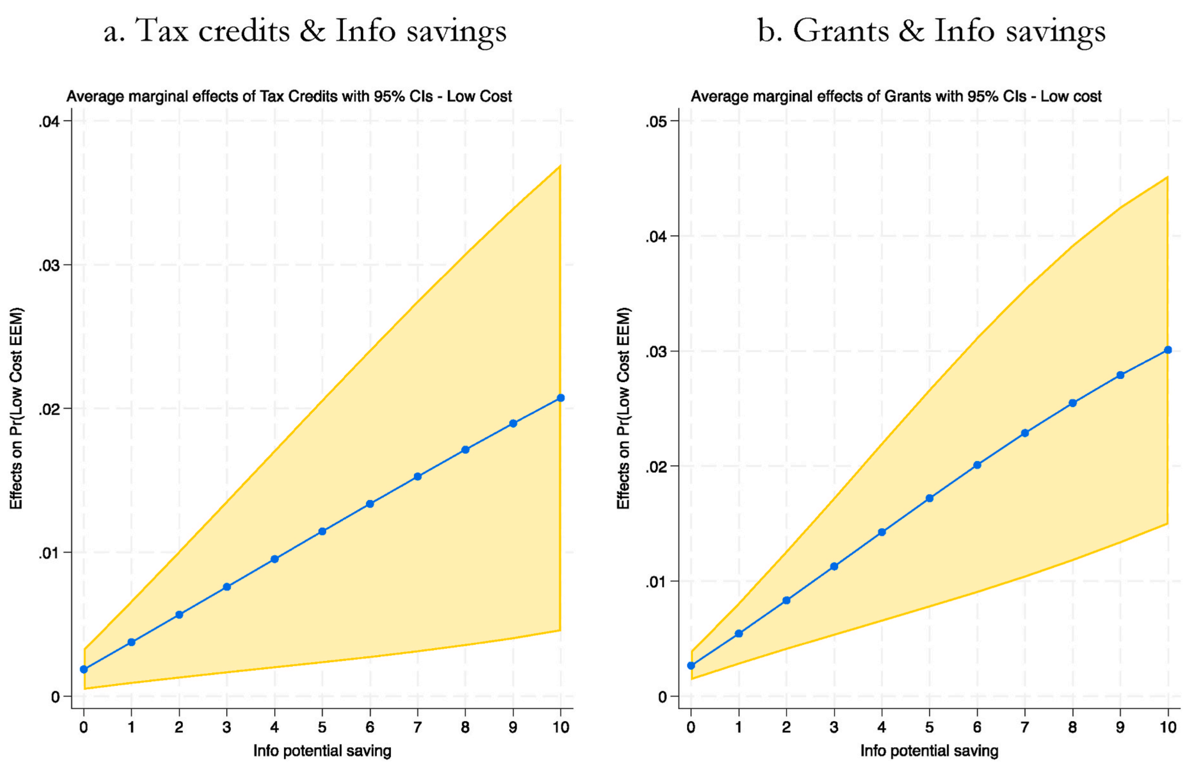

Fig. 9. Avg. marginal effects policy combinations (one + one) – adoption low-cost EE measures
Note: Left panel: The blue line represents the effects on the probability of adopting a low cost energy efficiency measure when governments implement tax credits jointly with the provision of information about savings (x-axis) (95th % CIs in yellow). Right panel: The blue line represents the effects on the probability of adopting a low cost energy efficiency measure when governments implement grants jointly with the provision of information about savings (x-axis) (95th % CIs in yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Own elaboration

effectively (Brown, 2001).

Therefore, based on these results, we cannot fully confirm our second hypotheses. While generally soft instruments in the form of easing administrative barriers and providing information on potential savings are important, differences can be found depending on the type of measures adopted by the households. The nature of the energy efficiency renovation will therefore be influenced by a diverse set of policy drivers. For coefficients of the regressions see Table A4 in the SI.1. In addition to this binomial discrete choice analysis, Table A5 in the SI.1 includes a multinomial logit model with a different specification of the dependent variable in multiple categories (0 = no EE adopted; 1 = adoption of low-cost measures, 2 = adoption of high-cost measures, 3 = any combination of low and high-cost measures). Results are similar and mostly consistent with those shown in Tables 3 and 4 [11] (See Table A5 in the SI. 1).

4.3. Policy mixes

In order to test our third hypothesis, we have run our estimations including policy interactions (See Tables A6–A11 in the SI.1 for the tables with coefficients). Interesting results arise from the holistic analysis of policy combinations. First, in estimations included in Tables 3 and 4, the implementation of tax credits individually was not statistically significant (for the adoption of individual measures). However, tax credits in combination with both information about potential savings and/or in combination with measures that help easing some of the administrative barriers faced by households show a positive and statistically significant effect, increasing the probability of adoption of energy efficiency measures by households (See Fig. 6a and 6c). In particular, a maximum average marginal effect of around 2% can be found when combining tax credits and information about potential savings. Also, interactions with measures to easing administrative barriers could increase the maximum average marginal effect up to around 2.4%. A similar effect can be found with the involvement of Utilities. As mentioned in the literature review and in the introduction, some instruments to foster energy efficiency adoption in households involve the implementation of energy efficiency obligations in utilities. Then, the energy companies need to implement the measures at the household level. While barriers due to lack of trust (Przepiorka and Horne, 2020) may appear when governments use this kind of instruments, the combination of information about savings, easing administrative barriers and the involvement of utilities also generate positive and statistically significant impacts on the probability of adoption of particular energy efficiency measures at the household level. While maximum average marginal effects are smaller than for other policy instruments and/or combinations of instruments, we can find average marginal effects over 1.5% when implementing in parallel the aforementioned three policy instruments (See Fig. 6e).

Importantly, the combination of instruments can also reinforce the positive effect of individual policies that are statistically significant and positive when implemented as standalone measures. This is particularly the case of grants for the adoption of energy efficiency measures. The implementation of grants in combination with information about potential savings and/or with the implementation of policies that reduces

[11] While the reported results are similar, attention must be paid to the fact that the decision of installing a combination of energy efficiency measures (both, those of the same typology and/or of different costs) may not be compliant with the assumption of independence of irrelevant alternatives. With a multinomial logit model, this assumption could be unrealistic leading to potential biases in the estimates. This is the main reason why the preferred approach in this paper is that based on binomial discrete choice models as the assumption of independence of irrelevant alternative is not relevant.

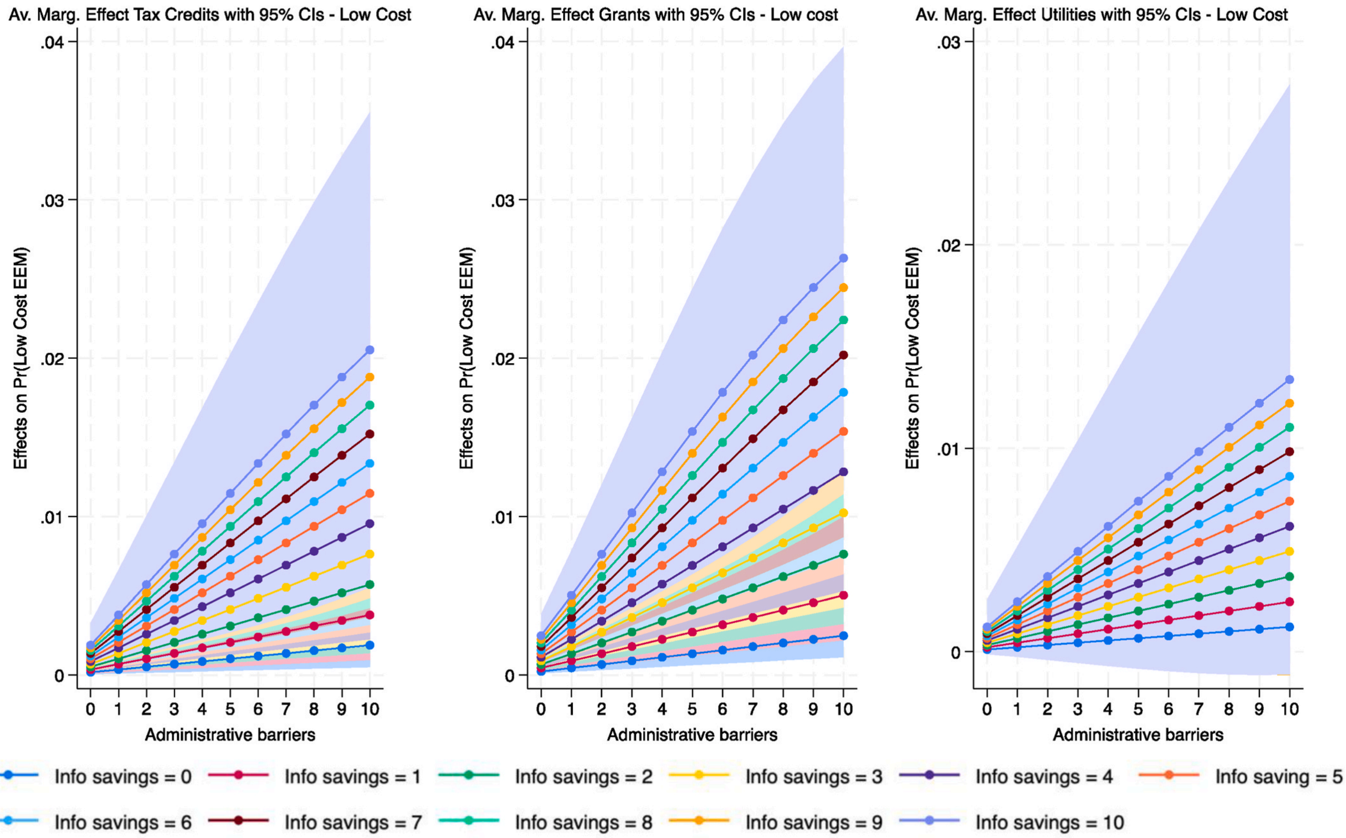

Fig. 10. Average marginal effects of policy combinations (>2) – adoption of low-cost EE measures
Note: Left panel: The colour lines from blue (bottom) to purple (up) represent the effects on the probability of adopting a low cost energy efficiency measure when government implement tax credits jointly with the easing of administrative barriers (x-axis) and with the scale of preferences by households in regards to information about savings (colour lines) from 0 (blue bottom – very unlikely to adopt an energy efficiency measure if the government put in place policies based on information about the potential savings of the particular energy efficiency measures) to 10 (purple up – very likely to adopt an energy efficiency measure if the government put in place policies based on information about the potential savings of the particular energy efficiency). The center panel and right panel present the same information that the left panel but for grants and the involvement of utilities together with the easing of administrative barriers (x-axes) and the provision of information (colour lines from 0 to 10) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: own elaboration

the administrative barriers associated to installing EE measures is positive and statistically significant (See. Fig. 6b and d). This reinforces what many authors and policy makers have been advocating for during the last decades i.e. how important policy mixes are when it comes to overcoming multiple market failures (Anadon et al., 2022). Policy mixes allow for a more comprehensive approach to addressing complex issues where multiple market failures e.g. environmental externalities, technological externalities and/or problems of asymmetric information arise (Rogge and Reichardt, 2016; Kern et al., 2019).

A closer analysis to policy interactions when considering low-cost and high-cost energy efficiency measures also reflect that the combination of policies may increase the probability of adopting energy efficiency measures at the household level through potential mixes of policy instruments that individually do not generate positive statistically significant effects (See Tables A8–A11 in the appendix for coefficients).

In our baseline estimations on high-cost measures, we have observed statistically significant effects principally for easing administrative barriers. This is due to the fact that traditionally high-cost measures are installed by households in the higher deciles of income with lower budgetary constraints. Yet, and interestingly when considering policy mixes, tax credits, grants and importantly loans in combination with information about potential savings and easing administrative barriers show positive and statistically significant impacts in the adoption of high-cost EE measures. The same happens with instruments like energy efficiency obligations instrumentalised through the participation of utilities. Figs. 7 and 8 shows the average marginal effects of the statistically significant policy combinations that would impulse the adoption of EE measures that require higher capital investments.

Results are similar for low-cost measures although policy mixes involving loans are not effective in encouraging the adoption on low-cost EE measures. As aforementioned, this may be the case as low-cost EE measure tend to be implemented mostly by low-income households who face higher budgetary constraints and find more difficult to get engaged with loans and/or soft loans that need to be returned (Figs. 9 and 10).

4.4. Robustness checks

The primary objective of this robustness check is to validate the stability and reliability of our initial findings regarding the adoption of energy efficiency technologies by households. In studies like this, particularly those involving surveys, it is quite typical to encounter instances of incomplete data. This usually happens when survey participants opt not to respond, indicate ignorance on the topic or are skipped over in the survey sequence. Consequently, these instances of missing data were not filled in with substitute values and were omitted from the analysis. Yet, in order to check the robustness of results, by applying both, imputed extra values in those variables included in the analysis that suffered from some missing values and a jackknife resampling technique, we assess the sensitivity of our estimates to the removal of

Table 5
Jackknife and imputed baseline estimation – marginal effects.

	(1)	(2)	(3)
Dep: Adopted EEM	Logit	Cloglog	Poisson
Tax credits	−0.00170	0.000685	0.0120
	(0.00676)	(0.00746)	(0.0266)
Loans	−0.00675	−0.00678	−0.0205
	(0.00444)	(0.00439)	(0.0175)
Grants	0.0141***	0.0152***	0.0606**
	(0.00519)	(0.00540)	(0.0263)
Release admin. barriers	0.0146**	0.0131*	0.0336
	(0.00725)	(0.00701)	(0.0314)
Utilities involvement	−0.0108**	−0.00843*	−0.0216
	(0.00498)	(0.00490)	(0.0202)
Info. Efficient use	−0.00858	−0.0102	−0.0333
	(0.00878)	(0.00852)	(0.0328)
Info. potential savings	0.0140	0.0170**	0.0777**
	(0.00876)	(0.00835)	(0.0371)
Info. Support schemes	0.000477	−0.000268	−0.00155
	(0.00867)	(0.00849)	(0.0338)
Higher EE. standards	0.0104	0.00682	0.0268
	(0.00764)	(0.00718)	(0.0325)
Stronger EE. standards	−0.00385	−0.00211	−0.0144
	(0.00763)	(0.00768)	(0.0338)
Awareness schemes	0.0192**	0.0165**	0.129***
	(0.00892)	(0.00819)	(0.0323)
Tenure (b. Owner)			
Renter	−0.188***	−0.191***	−0.948***
	(0.0308)	(0.0307)	(0.104)
Other	−0.181**	−0.177**	−1.035***
	(0.0802)	(0.0828)	(0.221)
Living period	0.0760***	0.0841***	0.503***
	(0.00720)	(0.00849)	(0.0520)
Dwelling characteristics controls	Included	Included	Included
EPC rating control	Included	Included	Included
Region control	Included	Included	Included
N	2084	2084	2084
pseudo R^2	0.2054		
AIC	2164.046	2161.459	7402.6
BIC	2395.37	2392.783	7634.0

Standard errors in parentheses * p < .10, **p < .05, ***p < .01.
Additional dwelling characteristics controls include: type of dwelling, year of construction, surface (sqf), number of bedrooms, HH size, old members living in the households, young members living in the households and income

Table 6
Jackknife and imputed estimations by type of EE measure – marginal effects.

	(1)	(2)	(3)	(4)
	Low-cost measures	Low-cost measures	High-cost measures	High-cost measures
Dep: Adopted EEM	Logit	Cloglog	Logit	Cloglog
Tax credits	0.000614	0.00196	0.00164	0.00541
	(0.00667)	(0.00663)	(0.00683)	(0.00730)
Loans	−0.00805*	−0.00790	−0.00145	−0.00203
	(0.00489)	(0.00483)	(0.00467)	(0.00458)
Grants	0.0151**	0.0149**	0.00736	0.00679
	(0.00585)	(0.00610)	(0.00563)	(0.00595)
Release admin. barriers	0.0120	0.0112	0.0125*	0.0126*
	(0.00813)	(0.00792)	(0.00756)	(0.00730)
Utilities involvement	−0.00680	−0.00530	−0.00488	−0.00340
	(0.00543)	(0.00535)	(0.00511)	(0.00508)
Info. Efficient use	−0.00316	−0.00498	−0.0128	−0.0130
	(0.00892)	(0.00864)	(0.00888)	(0.00852)
Info. potential savings	0.0199**	0.0199**	0.0138	0.0149*
	(0.00909)	(0.00892)	(0.00897)	(0.00861)
Info. Support schemes	−0.0121	−0.00892	0.00723	0.00540
	(0.00846)	(0.00827)	(0.00940)	(0.00882)
Higher EE. standards	0.00584	0.00454	0.0101	0.00809
	(0.00775)	(0.00765)	(0.00803)	(0.00746)
Stronger EE. standards	0.00340	0.00356	−0.0109	−0.00956
	(0.00803)	(0.00797)	(0.00815)	(0.00790)
Awareness schemes	0.0246***	0.0206**	0.0270***	0.0253***
	(0.00937)	(0.00916)	(0.00928)	(0.00870)
Tenure (b. Owner)				
Renter	−0.211***	−0.212***	−0.159***	−0.168***
	(0.0312)	(0.0315)	(0.0312)	(0.0319)
Other	−0.217***	−0.214**	−0.193**	−0.204**
	(0.0812)	(0.0858)	(0.0901)	(0.0905)
Living period	0.0826***	0.0915***	0.0790***	0.0882***
	(0.00888)	(0.0105)	(0.00807)	(0.00947)
Dwelling characteristics controls	Included	Included	Included	Included
EPC rating control	Included	Included	Included	Included
Region control	Included	Included	Included	Included
N	2084	2084	2084	2084
pseudo R^2	0.167		0.182	
AIC	2486.5	2489.4	2395.6	2394.9
BIC	2717.9	2720.7	2627.0	2626.2

Standard errors in parentheses * p < .10, **p < .05, ***p < .01.
Additional dwelling characteristics controls include: type of dwelling, year of construction, surface (sqf), number of bedrooms, HH size, old members living in the households, young members living in the households and income

individual observations, ensuring that our conclusions are not unduly influenced by specific data points (Tables 5 and 6).

The imputation process uses multivariate normal regression filling in missing data by assuming that the incomplete variables form a multivariate normal distribution. This way of imputing values models the joint distribution of the specified variables based on the observed data and then uses this model to predict missing values. This approach allows for the incorporation of correlations among multiple variables into the imputation process. Table A12 includes the descriptives of the imputed variables and a *t*-test showing that there are not statistically significant differences between imputed and non-imputed regressors. Tables A13 and A14 in the SI.1 include the regression coefficients.

As can be observed, results are consistent with the baseline analyses performed in this paper. The increase in the number of observations derived from the imputation exercise does not affect either the size or the level of significance of the policy drivers included in the analysis. Our results are robust as well to the utilization of a jackknife estimation.

5. Conclusion and policy implications

This paper has examined the impact of national-level EE policies on household adoption of EE measures and technologies and identifies policy drivers and household preferences in the UK. Our findings suggest that implementing governmental policy instruments at the national level through financial incentives such as grants and subsidies, coupled with information campaigns on potential energy savings, and the simplification of bureaucratic procedures can significantly increase the likelihood of families choosing and adopting energy-efficient solutions. Yet, the effectiveness of these policy instruments varies when comparing the uptake of less expensive EE interventions, such as installing loft insulation, versus more costly investments like heat pumps. The distinction in policy effectiveness between these different categories of EE measures is noteworthy. Crucially, our analysis underscores the vital importance of a synergistic approach to policy design. In the context of UK homes, the interplay of various policies, including tax incentives, can substantially bolster the implementation of EE measures in the residential sector. The complementary nature of these policies means that when they are employed in parallel as part of a policy mix, their capacity to drive the adoption of energy efficiency for domestic heating is amplified. In light of these findings, it is clear that while soft instruments and grants remain foundational, the complexity of EE adoption necessitates a more sophisticated and multifaceted policy approach. This approach should not only aim to reduce administrative barriers more effectively for high-cost measures but also leverage behavioral insights through information to create a more conducive environment for the adoption of EE interventions.

In regards to the implications derived from this study, our findings have important effects for policymakers seeking to enhance the effectiveness of national-level EE policies. While the UK has set out a range of policies and allocated substantial funds to improve energy efficiency and support the transition to clean energy, the fulfilment of environmental and energy goals requires more consistent and accelerated action, with a focus on enhancing the efficiency of existing infrastructure taking into considerations the needs of the citizens. In particular, the evolving landscape of energy efficiency adoption shows that governments can take advantage of the role of digitalization in, for example, enhancing information dissemination about savings. Also, it could be relevant to link housing policy to energy efficiency policy through the establishment of no stamp duty on zero carbon homes (HMRC, 2016; Peñasco and Anadón, 2023) or through modernising the Stamp Duty Land Tax to become an 'Energy Saving' Stamp Duty (UK Green Building Council, 2024). Furthermore, the integration of behavioral economics into policy design, focusing on nudging households towards more energy-efficient decisions, is gaining traction (Karlin et al., 2022). Additionally, the impact of social norms and community-based approaches has been identified as crucial in overcoming informational and trust barriers e.g. those related to the involvement of utilities, suggesting that policies fostering community engagement and peer-to-peer learning could enhance EE measure adoption (Goggins et al., 2022). Moreover, the differential impacts of high-cost versus low-cost EE measures continue to be a significant research focus, with recent studies advocating for more nuanced policy frameworks that account for these distinctions and the specific barriers each category faces (Gillingham et al., 2016).

Our results came from the information collected from a representative sample of UK households through an online survey. This strategy for data collection is therefore not free from limitations, above all related to the reliance on self-reported information and the potential appearance of response and/or sampling biases. While our survey is representative of the population at the national level, the segmentation of the sample in different categories e.g. by type of energy efficiency measures, may make difficult to establish adequate inferences. That is the main reason why we have opted for a segmentation in two types of energy efficiency measures i.e. high-cost vs. low-cost instead of breaking the sample in a larger range of energy efficiency technologies and interventions. This is an area of research that will deserve more attention in the future. Also, the increase in public involvement and the implementation of instruments to foster energy efficiency after the start of the war in Ukraine is not captured yet by the information in this survey. Further research evaluating the adoption of energy efficiency measures before and after the conflict is worth exploring.

CRediT authorship contribution statement

Cristina Peñasco: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares no conflict of interest in the development of this research study. This paper should not be reported as representing the views of the Banque de France (BdF). The views expressed are those of the authors and do not necessarily reflect those of the BdF.

Data availability

I have shared a link to my code and data submitted in Mendeley Penasco, Cristina (2024), From Policy to Practice: The Role of National Policy Instruments and Social Barriers in UK Energy Efficiency Adoption in households , Mendeley Data, V1, doi: 10.17632/zr2ddj7scw.1.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2024.114308.

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