Juggling the basics

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Original research article

Juggling the basics: How much does an income increase affect energy spending of low-income households in England?

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ABSTRACT

European governments have deployed targeted and untargeted financial support to protect vulnerable households from the impacts of the recent energy crisis. However, there is little knowledge of income elasticity of energy expenditure among households experiencing energy poverty. We therefore examine the link between energy expenditure and household income levels, considering a spectrum of factors including energy poverty status, energy efficiency of homes, and socio-demographics. We use England's official energy poverty definition, 'Low-income, low-energy-efficiency', and analyse the government's 'Fuel Poverty Dataset' from 2019. We find that, for all income groups, by far the greatest impact on energy expenditure is the dwelling's energy-efficiency rating, followed by floor area. An increase in income has negligible effects on energy expenditure for all income groups, but greatest for those in energy poverty, suggesting that even though most of their energy-oriented financial support is used for other pressing needs, this still offers some relief from energy poverty. We conclude that energy-efficiency improvements in homes would yield the most substantial and enduring financial benefits for these households, highlighting the need for targeted retrofitting policies. Additionally, older homeowners in energy poverty may need help to move into smaller, energy-efficient homes that are less expensive to heat.

1. Introduction

The ongoing cost of living crisis in the UK has intensified food and energy poverty, particularly affecting vulnerable households [1,2]. Estimates vary depending on the indicator employed, but if energy poverty were defined as being required to spend over 10 % of after-housing-cost income on domestic energy, the number of households surpassing this threshold more than doubled from 4.3 million in 2020 to 8.9 million in 2023 in England alone [3].[1] Although there may be uncertainties as to the accuracy of official statistics on energy poverty, there has clearly been a very substantial increase in the number of households having to cope with it in the last few years.

Sunikka-Blank and Galvin [4] demonstrated that single-parent households are notably at risk, as they tend to report a higher frequency of poor conditions in their homes, including issues such as a leaking roof, mould, damp walls, floors or foundations, and rot in window.

Boardman [5] pioneered the study of energy poverty, commonly referred to as fuel poverty in the UK, and defined it as the situation where a household is required to spend 10 % or more of its income on energy to achieve sufficient thermal comfort in the home. Following this, a widespread debate has emerged over the best way to measure energy poverty, with some scepticism as to whether there can ever be a universally agreed definition of energy poverty [6], or whether identifying households vulnerable to energy poverty will necessarily lead to well-targeted interventions capable of substantially mitigating it [7]. Over the years, the UK government has shifted from the 10 % indicator to Low Income High Cost (LIHC), and currently uses the Low Income Low Energy Efficiency (LILEE) standard to identify energy poverty in England [8].

Regardless of one's preferred definition of energy poverty, it is widely recognised that energy poverty is influenced by four key factors: household income, the energy efficiency of the housing, energy prices, and the characteristics of the household members [9,10].

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[1] Projections indicate a decline starting in 2024 as prices are expected to decrease.

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An area not thoroughly explored is the income elasticity of energy demand in this context: by what percentage does energy demand increase for each percentage increase in income? There is evidence that energy demand typically increases alongside income but not proportionally, which is partly attributed to more money being spent directly on energy and partly to the ability of wealthier households to invest in modern, energy-efficient technologies [11,12]. However, the literature does not extensively differentiate the income elasticity of energy demand among low-income households, nor distinguish between those in and not in energy poverty. This oversight is significant, as a nuanced understanding of these dynamics is vital for projecting the environmental impact of policy interventions and for formulating strategies that alleviate energy poverty without exacerbating environmental harm.

Accordingly, this study investigates the relationship between energy expenditure and household income categories, paying particular attention to those in energy poverty. It explores whether and how changes in income correlate with changing patterns of energy consumption (the income elasticity of energy consumption), alongside a broader set of factors such as a dwelling's energy performance and sociodemographic features. Using the results of this analysis, the study also aims to evaluate the extent to which energy demand is prioritised by different categories of households: those on high incomes, those on low and middle incomes, and those experiencing energy poverty according to the LILEE definition, namely households with <60 % of equivalised[2] household disposable income after fiscal transfers and housing costs, living in a dwelling with energy efficiency band D-G.[3]

Section 2 reviews existing literature on energy demand elasticities, focusing on income elasticity while also considering price elasticity, and discussing their significance for policy. Section 3 details the data sources and methodology used in the study, leading to insights into how changes in income affect energy spending across various income groups, energy poverty levels, and household characteristics. Section 4 discusses these findings within the framework of current energy efficiency and energy poverty alleviation policies in the UK. Section 6 concludes by offering recommendations for policy interventions and suggesting areas for future research.

2. Literature and policy review

2.1. Evidence on income elasticity of energy demand

Energy poverty, as a concept, aims to capture a specific form of deprivation where households find themselves unable to cover the costs of essential energy for basic needs such as heating, cooking, and lighting [13,14]. The concept underscores the intersection of energy policy, social equity, and health implications, such as excess winter mortality among vulnerable households [15,16]. The term's usefulness may differ by context and the prevailing policy discourse within a country. In the UK, the term energy poverty, often used interchangeably with the term fuel poverty, is widely used in policymaking and media. The definition of energy poverty is operationalised through specific metrics, such as the Low Income Low Energy Efficiency (LILEE) indicator, noted above, that are used to improve and evaluate the targeting of policy interventions [17].

However, some governments do not accept the notion of energy poverty. An example is Germany, which focuses instead on reducing poverty. As Andreas Feicht, former Secretary of State for the Federal Ministry of the Economy and Climate Protection explains:

"There is no generally valid definition for the term 'energy poverty'. The Federal Government pursues a holistic approach to assessing poverty and, accordingly, to combating poverty, which does not focus on individual elements of need." (Author's translation of [18]). Interestingly, in cold Nordic countries energy poverty is not widely recognised as a significant issue, due to developed energy infrastructure, energy efficient housing, and strong social security systems. In Finland, for example, energy poverty is not formally mentioned in the public debate, nor is there any definition of or approach to energy poverty within policymaking [19]. Similarly, in Sweden energy poverty is treated within the broader context of social policy, although temporary measures, such as subsidies, were implemented during the 2021–2022 energy crisis to help all households with increased energy prices.

A central concept explored in this paper is the income elasticity of energy demand: the percentage increase in energy demand that is associated with a 1 % increase in income [20]. This is distinct from the more extensively studied price elasticity of demand, which assesses how changes in energy prices affect household energy demand [21]. Evidence on price elasticity is more abundant, though results vary greatly across different studies, types of energy, and time frames [22]. In the UK, for instance, a 1 % rise in natural gas prices led to a 0.20 % decrease in energy demand in the short term and a 0.28 % decrease in the long term from 1990 to 2007 [23]. Household energy demand, especially for electricity, is often price inelastic in the short term due to it serving essential needs. This implies that even as energy prices rise, the demand for energy remains relatively stable, placing especially low-income households at risk of energy poverty [24]. Fry et al. [25] demonstrated that in Australia, low-income households tend to prioritise energy over food when prices rise, but also found evidence of heterogeneity among low income households in response to price increases.

The study of income elasticity of energy demand, particularly for space heating, has evolved significantly over the decades. Initially, Scott [26] reported high income elasticity for heating demand, approaching unity; however, subsequent research, such as Gillingham and Hagemann [27], Nesbakken [28], and Meier et al. [12], found that the income elasticity of energy demand is generally much smaller than unity, characterizing energy as a necessary good. The complexity of the debate increases when distinguishing between income groups. For instance, Baker and Blundell [29] and Harold et al. [30] found that energy demand of low-income households in the UK and Ireland, respectively, is more responsive to income changes, whereas Nesbakken [28] and Schulte and Heindl [31] observed the opposite in Norway and Germany, with higher income elasticity among higher income groups. A U-shaped income elasticity curve, with low-income households having high elasticity as they want to meet basic energy requirements, middle-income households low elasticity as they are less inclined to allocate additional income to energy, and high-income households high elasticity as they demonstrate demand for luxury energy services is found in in Spain [32] and the Philippines [33], but contrasts with the inverted U-shape observed in the US [34].

Compared to other spending categories, energy expenditure in the UK shows less variation based on income than any other spending category [35]. Heating is considered a basic need, with limited substitutes. Therefore, high energy prices disproportionally affect low-income households. Such dynamics can lead to self-disconnections among households on prepaid meters [36] or self-rationing prebound effects, where particularly low-income households in energy inefficient dwellings deliberately limit their energy use to spend money on other essential areas [37]. Notably, self-rationing is not always a result of economic drivers and exists across all income groups, including middle- and high-income households. This can be related to under-occupied and large, partially unheated spaces. It is therefore important to distinguish between 'forced/harmful self-rationing' and 'voluntary/rationalised self-rationing' [38–40].

However, when discussing income elasticities of space heating demand, Douthitt [41] emphasised that dwelling attributes, rather than socioeconomic characteristics, play a more decisive role in consumption patterns, a view supported by more recent studies [42–46]. Therefore,

[2] "equivalised" means adjusted for household size. In 2023 this was £17,300/y, and £17,105 in 2019, the date of the data survey.

[3] This represents a SAP12 rating of 70 or below.

the relationship between income, energy demand, and energy efficiency improvements is pivotal in this field of research. Karpinska and Śmiech [47] found that higher income Polish households tend to live in more energy-efficient homes and use cleaner heating fuels, whereas low-income households in inefficient dwellings cut on energy use to satisfy other basic needs. Similarly, Rhiger Hansen and Gram-Hanssen [48] found that low-income families in energy-inefficient homes had significantly lower heating demands than expected, reflecting frugal heating practices. Conversely, households with higher incomes have the means to invest in energy-efficient appliances, better insulation, and renewable energy sources, reducing energy consumption while enhancing living standards [49]. Finally, tenure reveals a similar disparity: tenants bear higher energy costs when landlords, particularly in countries like the UK where there is no obligation to invest in energy efficiency, neglect such improvements [50,51].

Despite extensive research on income elasticity of energy demand, significant gaps remain, particularly regarding the differentiated impacts across various household income categories and the interplay with dwelling characteristics and energy performance. Most studies focus on broad aggregate measures, neglecting the heterogeneity within low-income groups and the specific challenges faced by households living in energy-inefficient dwellings. Charlier and Kahouli [52], who primarily focus on price elasticity, suggest a higher income elasticity for energy-poor households compared to non-energy-poor households. However, this is based on expenditure-based rather than energy efficiency-based energy poverty indicators, and does not compare energy-poor households with other low-income households that are not in energy poverty. This paper addresses these gaps by offering a nuanced analysis that employs an energy poverty indicator combining these factors, aiming to identify the specific income elasticity for households with both low income and energy-inefficient dwellings.

2.2. UK's policy response to energy poverty

There have been and are a variety of policy measures targeting energy poverty across Europe (see e.g. [53,54,55]), including one-off ad hoc payments and energy costs subsidies, alongside long-term policies of improving existing housing with thermal insulation. How does income elasticity of energy expenditure relate to recent UK policies?

The UK government recently addressed energy poverty in their updated strategy 'Sustainable warmth: protecting vulnerable households in England', published in response to a consultation to update the 2015 energy poverty strategy. The updated strategy emphasises the government's commitment to the 2030 target for improving fuel poor homes to a minimum energy efficiency rating of Band C, and to add a fourth guiding principle focused on sustainability, updating the metric to simplify the identification and measurement of fuel poverty [56].

Alongside energy efficiency strategies, the UK government has introduced several welfare payments to alleviate energy poverty over the years, including the Winter Fuel Payment, Warm Homes Discount, and Cold Weather Payments [57]. The Winter Fuel Payment, available across the UK to those above state pension age, provides an annual sum of £250–£600 (depending on circumstances) directly into recipients' bank accounts (but see comment below on recent cuts). In 2022, 11.6 million pensioners received a total of over £4.5 billion in support. Cold Weather Payments, applicable in England, Wales, and Scotland, deposit £25 into bank accounts of eligible benefit recipients, such as those on Pension Credit or Universal Credit, during periods of extreme cold. The reformed Warm Homes Discount, available in England, Wales, and Scotland, offers automated rebates that reduce energy bills or that credit prepayment meters for low-income pensioners (core group 1) and certain benefit recipients living in high-energy-cost dwellings (core group 2). In England and Wales, both core groups receive the discount automatically, while in Scotland, core group 1 benefits automatically, and core group 2 must apply for the discount.

The UK government's response to the energy price surge in 2022 included additional measures such as a £200 upfront discount on bills, a £150 Council Tax rebate for approximately 80 % of households in England, and extra funding for local authorities. The Energy Price Guarantee, introduced in October 2022, aimed to cap the unit rates for electricity and gas below Ofgem's official price cap level, reducing the 'average' household's annual bill to £2500 in Great Britain and around £2109 in Northern Ireland.[4] This guarantee also provided a small discount for households using prepayment meters (PPMs) in Great Britain, aligning their charges with those of direct debit customers; however, this did not apply to Northern Ireland due to its distinct energy market. Additionally, every household in the UK automatically received a discount of £400 on their energy bills over the winter of 2022/2023 through the Energy Bill Support Scheme [58], though this discount was not repeated in the subsequent winter.

A recent policy change by the Labour government involves limiting Winter Fuel Payments to pensioners who do not receive pension credit, effectively removing the benefit for single pensioners with incomes above approximately £11,300/y, pensioner couples with incomes above £17,300, and others with savings considered too high. This could significantly impact energy poverty by the LILEE indicator, since these income thresholds fall below the low-income level used in this measure, which is set at 60 % of the median equivalised disposable income. Although many pensioners may manage without this support, some risk being overlooked, particularly since this group is already vulnerable to energy poverty.

There is lack of understanding of the effectiveness of energy support payments, what the payments are actually used for, and whether there is a gap between policy intentions and actual outcomes. There is little knowledge on income elasticity of energy demand in low-income households and households in energy poverty in the UK: whether an increase in household income will lead to more spending on energy among these households.

In the UK in 2023 the average homeowner spent £25 per week on energy costs and £50 per week on housing costs [59], across all income groups. However, low-income households, especially in the private rental sector [60], spent disproportionally more on housing and energy compared to middle- and high-income households. The lowest decile income group spent on average 26 % of their total expenditure specifically on housing and energy, whereas the highest income group (top 10 % earners) spent on average 11 % [59].

Low-income households are also impacted by the cost of digital services. 9 % of England's poorest households have to cut back on essentials like food or clothing to afford phone or home internet costs [61]. 17 % of these households frequently run out of data and the bottom 10 % of the income distribution group in England may spend around 19 % of their income on fixed broadband tariffs after essential costs, at the expense of other basic needs like food and energy. Since low-income households are short of cash for these basic needs, they may have higher priorities to spend welfare payments on than energy.

Further, the statistics can hide the fact that many low-income households have outstanding debts, including owing money to a friend or family member. According to the Trussell Trust [62], 90 % of people using a food bank (many of whom are in energy poverty) have various kinds of debts. 60 % of food bank users have less than £100 in savings and therefore no liquidity buffer to respond to unexpected demands like dentist payments, car repairs – or increased energy prices. If there is spare income, part of household expenditure will go towards paying off the debt.

Another significant issue is the striking disparity in housing costs between the private rental sector and owner-occupied homes. In the UK, an average household in the owner-occupied sector spent, on average,

[4] According to Ofgem, the typical household in Great Britain uses approximately 2700 kWh of electricity and 11,500 kWh of gas per year (see https://www.ofgem.gov.uk/average-gas-and-electricity-usage).

£53 per week on housing costs (there is a large proportion of older home owners whose mortgages have been paid off), whereas a household who is a social renter spent £104 per week, and an average household renting in the private sector spent £199 per week [59]. This means that private renters in the UK on average spend four times as much on housing as owner-occupiers, but also face lower housing standards and lower energy efficiency. There is often a lack of compliance with the Decent Homes Standard and the requirement to have an Energy Performance Certificate (as is the case in the rest of Western Europe, see [63]). The UK decarbonisation policy in the housing sector has focused on 'innovations' and a business-led approach, but factors such as a poor historic record in retrofit rate, very slow energy efficiency improvements and increased energy costs for households are recognised in the government's own Net Zero Review [64]. The Review promotes heat pumps, a solar rooftop installation 'revolution' and banning gas boilers as acceleration strategies towards net zero, but does not discuss how low-income households living in rental properties will be able to access such installations.

There are, then, a large number of diverse policy interventions to seek to address energy poverty. Some of these are direct payments designed to enable low-income households to increase their energy expenditure. The extent to which these have this effect depends crucially on the income elasticity of energy expenditure among low-income households, and more particularly among households in energy poverty. This paper therefore investigates this metric based on recent countrywide data.

3. Method and data

3.1. Rationale and regression strategy

This study utilizes the 'Fuel Poverty Dataset', provided by the UK's now-disbanded Department for Business, Energy and Industrial Strategy (BEIS). It is derived from the 2019 English Housing Survey (EHS), and the data collection period spans from April 2018 and March 2020, with BEIS designating April 2019 as the reference point for analysis. The dataset consists of 11,974 observations, each featuring 43 variables.

Initially, we performed a comprehensive series of multivariate analyses aimed at identifying variables significantly associated with the annual demand for (i.e., expenditure on) space heating energy.[5] This involved, first, a set of stepwise regressions considering all variables potentially linked to heating energy consumption. Through this process, we systematically excluded variables that either lacked statistical significance or exhibited multicollinearity, defined by a variance inflation factor (VIF) exceeding 3.5. Consequently, from an initial list of 59 variables, we narrowed down to 14 variables of interest, namely:

- Income after housing costs and tax and welfare transfers (Symbol: AHCIncome)
- Floor area, in m^2 (FloorM2)
- Energy efficiency rating according to the Standard Assessment Procedure (SAP12)
- Whether the dwelling is solid walled *and* does not have solid wall insulation (solid_Wall_Unins)
- Whether the dwelling has gas heating (gas_Heating)
- Whether it has central heating (central_Heating)
- Whether the main householder is aged 16–24 (age16 to24)
- Whether the main householder is working (working)
- Whether there is a sick household member (sick_Member)
- Whether the occupants are a couple with dependents (couple_w_Dependents)
- Whether it is a one-person household (one_Person)
- Whether it is a private rental (private_Rental)
- Whether it is an owner-occupier household (owner_Occupier)

It may be asked why we did not include "household size", i.e., number of persons in the household, in the final list of variables of interest. We included it in the initial regressions but it was eliminated in the stepwise regressions as it showed high multi-collinearity with other variables, especially "one-person household". Hence the effect of "household size" was masking the effect of "one-person household", and only one of these could be included in the definitive regression. We comment again on this in the Results section.

It is also important to note that the household income figure in the database is the "Equivalised after housing costs annual income (£)". The description of this variable given in the dataset documentation is "the full annual income of the household, which is based on the net income, including housing benefit, SMI, MPPI and net council tax payments. This includes income for the whole household from all sources, including benefits and savings and investments" [66].

Subsequent regression analysis of these surviving variables against space heating cost, using all observations, yielded a maximum VIF score of 1.98 and a peak p-value of 0.065 (as detailed in Table 3 in Section 4). The aim of this and subsequent regressions was to find the variables most strongly associated with annual heating energy cost. It is important note that while the regression coefficients are influenced by differing units of measurement for the variables, comparing the coefficients within a specific regression does not indicate the strength of the association. The t-statistics, however, do indicate the comparative strengths of the associations, and therefore these were compared. While normalised regression coefficients could also have been employed, their Beta values proportionally align with the t-statistics.

Further analyses involved applying transformations to variables to achieve normal distributions for each numerical variable, as discussed in Section 3.3.

The next phase focused on performing separate regressions for distinct income groups. This included low-income households, defined as those earning below 60 % of the national median income after welfare and fiscal transfers and housing costs, i.e. less than £17,105/y in 2019. Additionally, regressions were conducted for 'high-income households', with incomes equal to or exceeding £17,105/y. The low-income band was further divided into 'very low-income households' (AHCIncome < £9000/year) and 'middle-low-income households' (AHCIncome between £9000 and £17,105/year).

Finally, low-income households were segmented based on their energy poverty status by the LILEE indicator, which identifies energy poverty through a combination of low income and a SAP12 rating below 70. Low-income households with SAP12 < 70 were classified as in energy poverty, while those with SAP12 ≥ 70 were classified as low-income but not in energy poverty. Subsequent regressions were conducted on these two newly segmented groups to further examine the nuances of energy poverty's impact on income elasticity of energy expenditure.

This granular approach allowed us to compare t-statistic profiles across various regressions, using both actual and transformed variables. Such comparisons were instrumental in pinpointing the variables with the most significant impact on space heating costs across different income groups. Moreover, by scrutinising the regression coefficients for specific variables, we could quantify the effect of a one-unit change, or in some cases a 1 % change, in each variable on the annual space heating cost. This methodology not only provided insights into the dynamics influencing heating costs but also highlighted the differential effects across income strata.

[5] With a multivariate analysis we can isolate the effect of each independent variable on the dependent variable, which in this case is energy expenditure. So, for example, although it is already well known that house size influences energy expenditure, the multivariate analysis prevents this from polluting the result for the influence of income on energy expenditure. The regression coefficients for each of the different factors influencing energy expenditure thereby indicate that factor's effect if all the other factors are held constant.

Table 1
Descriptive statistics: relevant variables for different categories of household and dwelling.

	All households		Higher-income households (AHCIncome ≥ 17,105)		Low-income households (AHCIncome < 17,105)		Very low-income households (AHCIncome < 9000)		Mid-low-income households (AHCIncome 9000 ≤ 17,105)	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
space heating cost	540	319	580	347	483	264	470	267	488	262
AHCIncome	24,434	17,132	33,700	16,507	10,984	4298	5405	2808	13,189	2341
FloorM2	78.7	27.1	84.3	27.5	70.4	24.3	68.9	25.1	71.1	23.9
SAP12	65.7	10.4	64.9	11.0	66.9	9.5	66.9	9.9	66.8	9.4
solid Wall Unins	0.226	0.418	0.228	0.419	0.223	0.417	0.253	0.435	0.212	0.409
gas Heating	0.852	0.356	0.853	0.354	0.850	0.358	0.831	0.375	0.857	0.350
central Heating	0.919	0.272	0.924	0.265	0.913	0.282	0.897	0.304	0.919	0.273
age16to24	0.023	0.151	0.013	0.115	0.038	0.191	0.068	0.252	0.026	0.159
working	0.548	0.498	0.631	0.483	0.428	0.495	0.353	0.478	0.458	0.498
sick Member	0.416	0.493	0.341	0.474	0.524	0.499	0.548	0.498	0.515	0.500
couple w. Dependents	0.208	0.406	0.189	0.392	0.235	0.424	0.204	0.403	0.247	0.431
one Person	0.310	0.462	0.289	0.453	0.340	0.474	0.416	0.493	0.310	0.462
private Rental	0.202	0.402	0.172	0.377	0.247	0.431	0.307	0.461	0.223	0.416
owner Occupier	0.448	0.497	0.628	0.483	0.187	0.390	0.147	0.354	0.203	0.402
observations	11,974		7090		4884		1384		3500	

Table 2
Descriptive statistics, households in energy poverty by the LILEE indicator and low-income households not in energy poverty.

	Households in energy poverty by LILEE indicator		Low-income households not in energy poverty	
Variable	Mean	Std. Dev.	Mean	Std. Dev.
space heating cost	642	320	383	153
AHCIncome	9961	3960	11,619	4376
FloorM2	73.9	24.9	68.3	23.7
SAP12	59.5	9.8	71.4	5.7
solid Wall Unins	0.366	0.482	0.135	0.342
gas Heating	0.798	0.402	0.882	0.323
central Heating	0.869	0.338	0.940	0.238
age16to24	0.038	0.191	0.038	0.191
working	0.459	0.498	0.409	0.492
sick Member	0.502	0.500	0.539	0.499
couple w. Dependents	0.267	0.442	0.215	0.411
one Person	0.287	0.452	0.373	0.484
private Rental	0.346	0.476	0.185	0.389
owner Occupier	0.229	0.420	0.160	0.367
observations	1872		3012	

A factor we have not included is an energy cost equivalation based on the number and type of householders. After wide ranging public discussion, the Hills Fuel Poverty Review [67] suggested that a dwelling's heating demand should be adjusted for the type of household. In one suggested approach, the energy demand of a dwelling in which a couple with dependent children live is regarded as 1.15 times that of a similar dwelling in which a couple without children live. The suggested range is 0.82–1.15. In our statistical analysis, however, we found that the impact of number of householders is very small compared to other factors. Rather than interfere with the raw data for such small gain, we decided to leave this out of the reckoning.

3.2. Descriptive statistics

The descriptive statistics of space heating cost and the 16 associated variables are presented in Table 1, covering all households and each of the four income segments. Meanwhile, Table 2 focuses on households classified as living in energy poverty according to the LILEE indicator, as well as low-income households not considered to be in energy poverty. These statistics are further explored alongside regression findings in Section 4. Note that aside from the first four variables, the remainder are binary dummy variables with values 1 or 0. Consequently, the mean for these variables reflects the proportion of households having specific characteristics. For instance, 63.1 % of high-income households have a working head-of-household, compared to only 35.3 % for very low-income households.

Note that Table 2 shows a very large difference in expenditure on energy between households in and not in energy poverty by the LILEE indicator, £642/y compared with £383/y. Although the latter are in homes with good SAP12 ratings, some may still be underheating due to their low income. While the LILEE indicator generally performs better than expenditure-based measures in identifying such households experiencing hidden energy poverty, it does not capture all cases of underheating (see discussion in [68–71]).

3.3. Shapes of the distributions

The variables representing space heating costs and AHCIncome are right skewed, but transforming these through natural logarithms yields close-to-normal distributions (see Figs. 1 and 2). Conversely, the SAP12 variable is left-skewed, and its cubed transformation achieves a normal distribution (see Fig. 3). The FloorM2 variable already approximates a normal distribution without the need for transformation.

This offers two distinct approaches for conducting the multivariate analyses. Initially the analyses were performed using the original untransformed data, facilitating straightforward interpretation of the results, despite potential inaccuracies. Subsequently, the analyses were repeated with the transformed variables, to assess the impact on the t-statistics and the overall analysis accuracy.

The results of the regressions were examined to draw conclusions about the parameters associated with higher or lower heating energy consumption, in two ways. First, within each specific group (high-income, low-income, etc.), the t-statistics indicated the relative impact of each variable on space heating consumption. Second, by comparing across the groups, the regression coefficients for each variable provided a basis for comparing their effects on space heating consumption the different income and energy poverty categories.

4. Results

4.1. Regression results for all observations

Table 3 presents the regression results for all observations using only the variables that remained after the stepwise process (hereinafter called the 'relevant variables'), without log and other transformations. These variables all have p-values below the threshold of 0.1, which, albeit

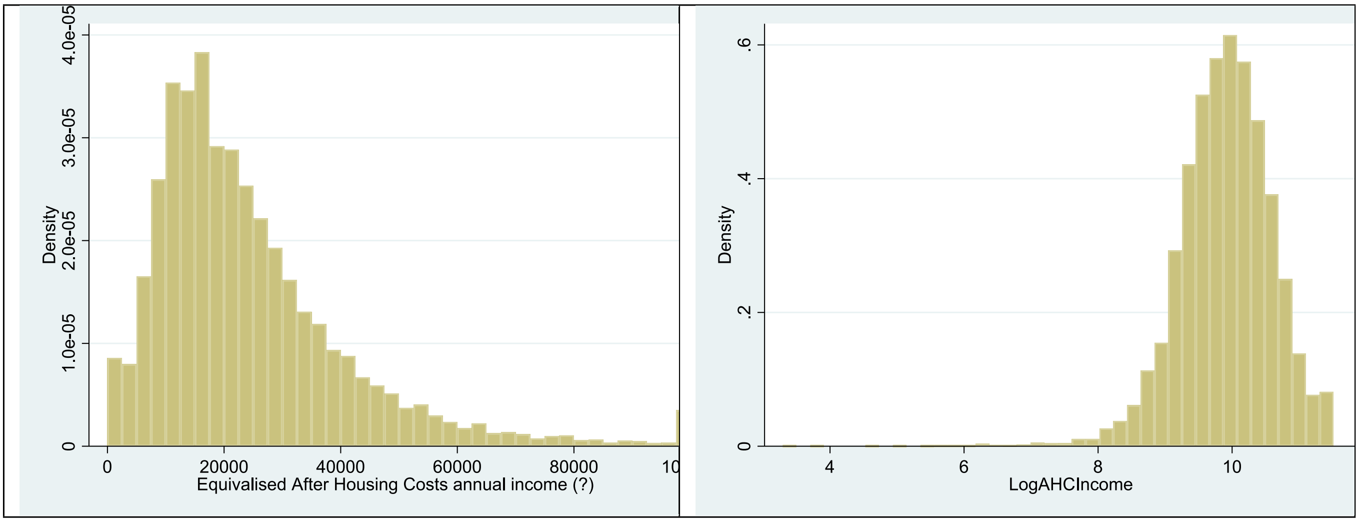

Fig. 1. Histograms of AHCIncome and Log(AHCIncome).

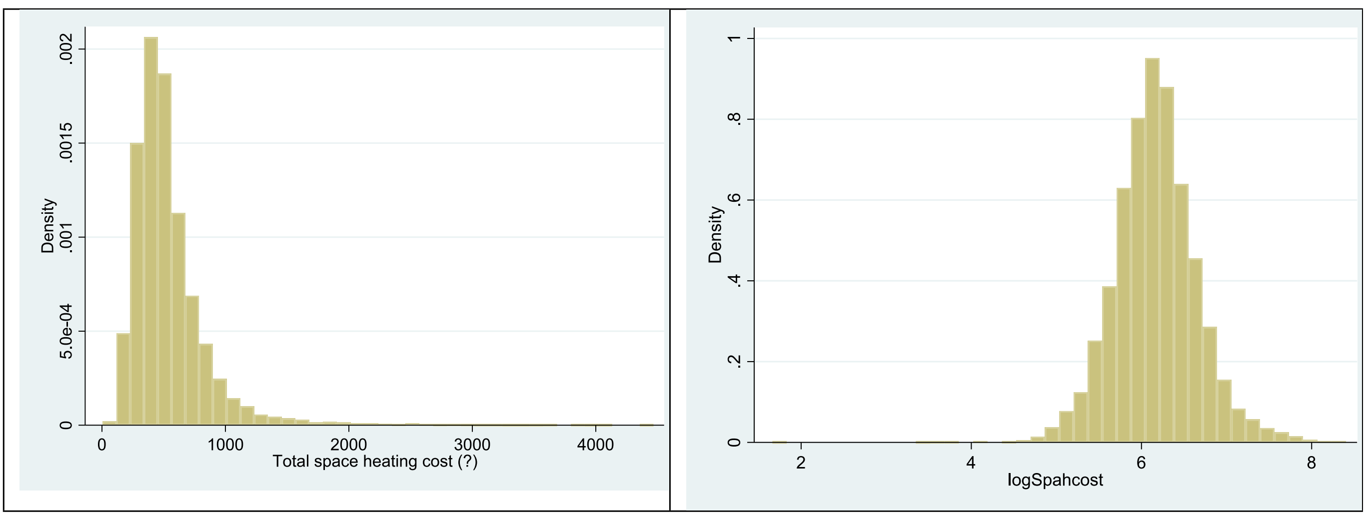

Fig. 2. Histograms of space heating cost and log(space heating cost).

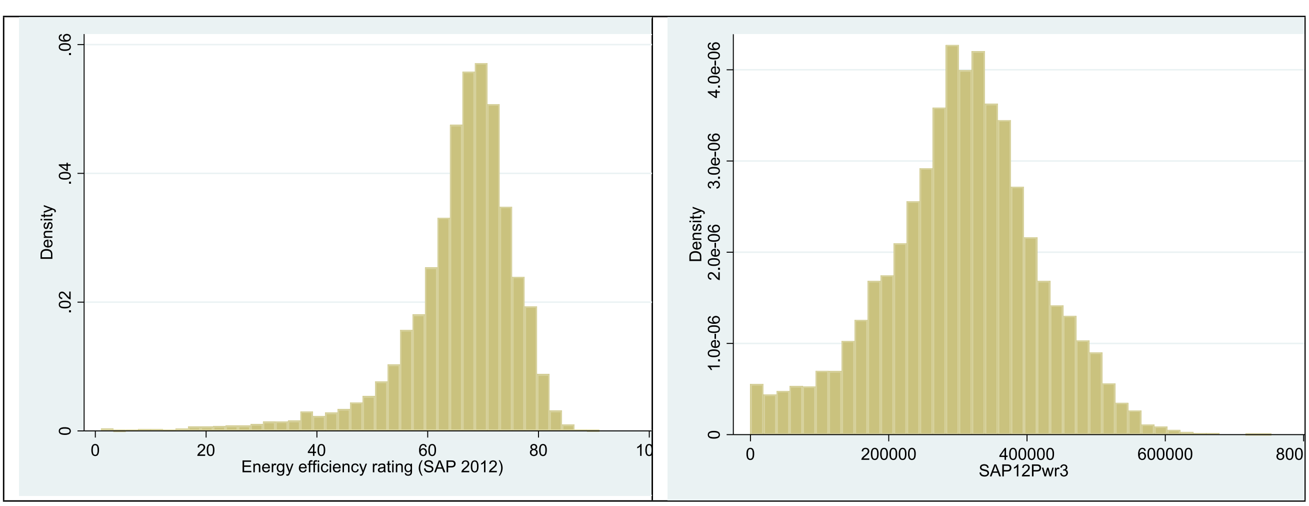

Fig. 3. Histograms of SAP12 and (SAP12)ˆ3.

Table 3
Regression results with relevant variables, for all households in the database.

Regressed against space heating cost	Coef.	Std. Err.	t	p-Value
AHCIncome	0.000998	0.000105	9.48	0
FloorM2	4.09	0.071	57.16	0
SAP12	−21.11	0.175	−120.5	0
solid Wall Unins	9.59	4.07	2.36	0.018
gas Heating	−68.08	6.04	−11.26	0
central Heating	−14.44	7.83	−1.84	0.065
age16to24	−33.41	10.36	−3.22	0.001
working	−10.88	3.64	−2.99	0.003
sick Member	8.75	3.38	2.59	0.01
couple w. Dependents	20.94	4.25	4.93	0
one Person	−39.49	3.81	−10.37	0
private Rental	−34.92	4.65	−7.51	0
owner Occupier	−19.19	4.29	−4.47	0
_cons	1677.36	13.50	124.25	0
F	0.000			
Adj R-Sq	0.726			
Observations	11,974			

somewhat arbitrary, denotes the degree of statistical significance we are using in this study.[6] Note that 15.6 % of the households represented in the database are in energy poverty by the LILEE indicator (1872 households out of 11,974).

In Table 3, each variable's regression coefficient gives the increase in annual space heating costs for an increase of 1 in the value of the variable. For example, an increase of £1/y in income (after housing costs and fiscal transfers) is associated with a marginal increase in heating costs of £0.000998/y (about one-tenth of a penny) A 1 m^2 increase in floor area is associated with an annual heating cost increase of £4.09/y, and each unit increase in SAP12 rating corresponds to a reduction in heating costs of £21.11/y.

The t-statistics provide a more nuanced understanding of each variable's impact on space heating costs. The larger the absolute value of the t-statistic, the bigger the impact.[7] Fig. 4 illustrates the t-statistics derived from regressions using actual values, transformed variables (natural logarithm of space heating cost and AHCIncome, cube of SAP12), and normalised variables. This set of displays shows minor differences in the relative impact of the most impactful variables regardless of which of the three methods is used. However, using the transformed variables (second graph), a clear point of difference is the impact of AHCIncome, which is shown to be even smaller, relative to other impacts, than when using the non-transformed data. We therefore use the transformed variables when displaying t-statistics from here on.

We commented in the methods section that the variable "household size" was eliminated in the stepwise regression process due to its high correlation with other variables. To explore this further, we performed an extra regression that includes "household size" along with the surviving variables. "One-person household" showed the larger absolute t-statistic value (−5.87 compared to 2.95) and was more strongly statistically significant (0.000 compared to 0.003). This confirmed that eliminating "household size" rather than "one-person household" was the correct procedure. Further, in this extra regression the variance inflation factor (VIF), which indicates multicollinearity, was high, at 4.01 for "household size". When we eliminated this variable, the highest VIF was 1.96, and the VIF for "One-person household" was very low, at 1.33.

4.2. Regression results for different income groups

Tables 4 and 5 provide a breakdown of the regression results for the distinct income brackets and for households identified as being in energy poverty according to the LILEE indicator, compared with low-income households not facing energy poverty. The p-values here indicate that not all variables show statistical significance in all income bands and categories, a point discussed further below in relation to the t-statistics.

In the analysis of regression coefficients for the most impactful variables across different income brackets and categories, a distinct pattern emerges in the response to energy efficiency improvements, as indicated by changes in the SAP12 rating. High income households exhibit the most pronounced response to a one-point increase in the SAP12 rating (i.e. a marginal energy efficiency improvement), with a reduction in annual space heating costs of £21.74/y, closely followed by households in energy poverty, which show a decrease of £21.59/y. Conversely, the response from very low-income households is somewhat muted at a £19.45/y reduction, and lowest among low-income households not experiencing energy poverty, at −£17.02/y. In other words, *living in energy poverty or having a high income significantly increases a household's adjustment in heating expenditures in response to improvements in their home's energy efficiency,* whereas having low-income but not being in energy poverty shows a more modest response.

A similar dynamic is observed in the reaction to an increase in floor area by 1 m^2. Households facing energy poverty demonstrate the greatest increase in annual space heating costs, at £5.04/y, suggesting a more substantial financial burden from larger living area. This compares with £4.18/y for high-income, £3.65/y for low-income, and £2.99/y for very low-income households not in energy poverty. This indicates that *low-income households overall are constrained in their ability to financially manage increased heating demands, but respond much more strongly if they are in energy poverty*.

Descriptive statistics in Tables 1 and 2 provide further context, revealing that high-income households have a relatively low (bad) SAP12 rating, at 64.9, while the average SAP12 rating for low- and low-mid income households is better, at around 66.9. The lowest average SAP12 rating, however, is for households in energy poverty, at 59.5, while the highest is for low-income households who are not in energy poverty, at 71.4. It seems, then, that *low energy efficiency (low SAP12 rating) is a far more decisive factor than income in determining energy poverty – though both do play a role*, since income after housing cosrts, welfare payments and tax transfers had to be below about £17,105/y in 2019 for a household to fit the LILEE definition of energy poverty.

High-income households also have the largest average floor area, averaging 84.3 m^2, compared to low-income households not in energy poverty, who have the smallest, at 68.3 m^2, followed closely by very low income households, at 68.9 m^2 *Households in energy poverty have a larger average floor area, at 73.9* m^2*, which may add to space heating difficulties.*

With regard to income after housing costs, tax and transfers (AHCIncome), households in energy poverty have the largest response to income: for each extra £/y of income, they spend an extra £0.00184/y on heating, whereas low-income households not in energy poverty spend have only about one-third this amount, at £0.000694/y. High-income households have the second-highest response, at £0.00157/y, while very low-income households spend only £0.00117/y, and low-mid-income households spend even less, at £0.000715/y. This suggests that *increasing the income of households in energy poverty has a positive effect on energy use.* Even though these responses are low for all income groups and categories, the response of households in energy poverty is the highest, even higher than that of high-income households.

We now examine the t-statistics (of the transformed variables) to see which variables have the biggest impact on space heating cost, for each income band and category.

Looking at the t-statistics in the regression tables and in Figs. 5–10, it is clear *that for all income bands and categories, by far the greatest impact on space heating expenditure is the SAP12 rating.* For all income bands and

[6] A p-value of 0.1 indicates that there is greater than a 10 % probability that the sign (+ or −) of the regression coefficient is the opposite, in the population, from its value in the sample, or that it is zero in the population.

[7] Note that the same is true for beta values if we were to use normalised variables in the regressions. There is a one-to-one relationship between the t-statistics for a non-normalised regression and the beta values for a normalised regression.

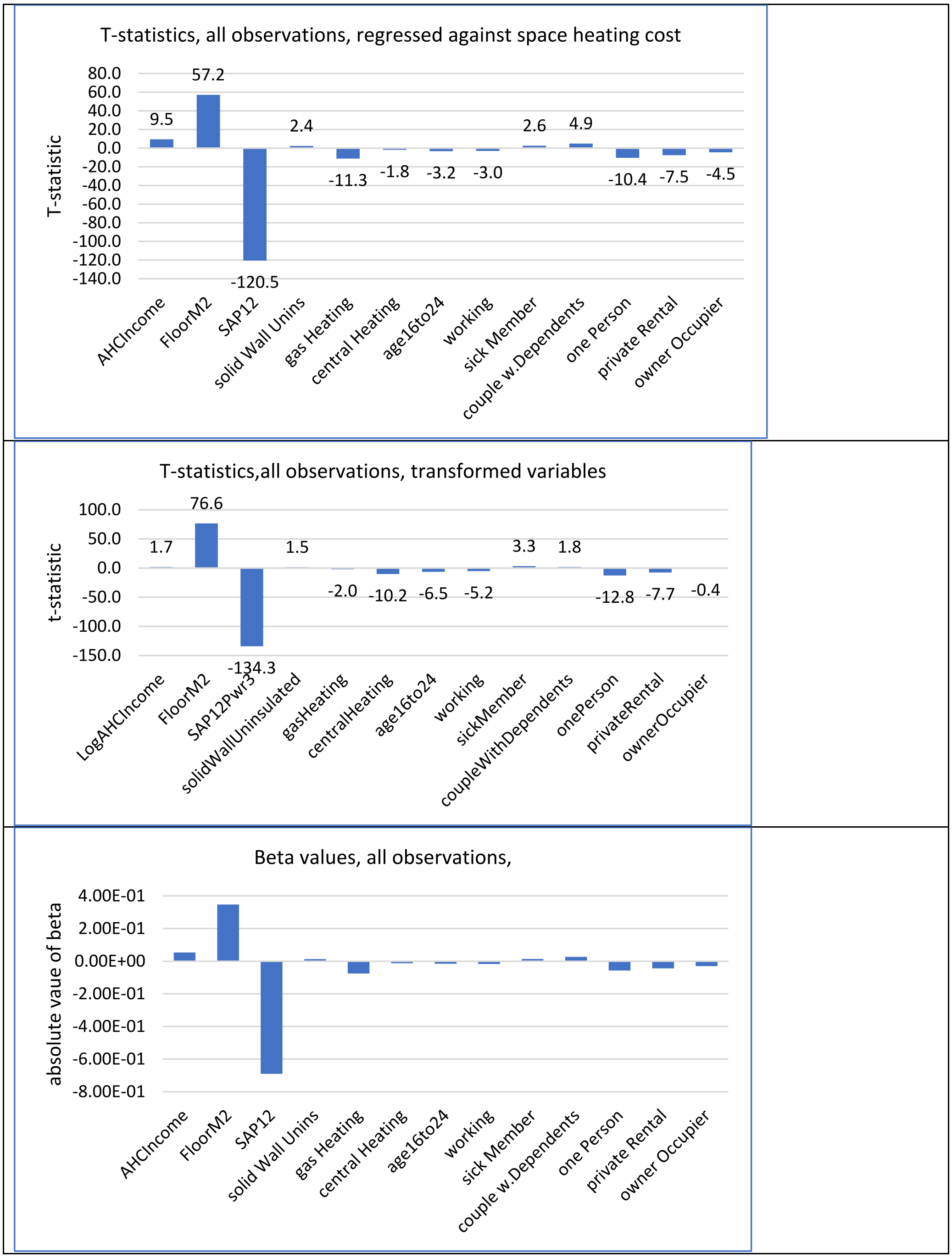

Fig. 4. T-statistics for regression of all observations, using untransformed and transformed variables, and beta values using untransformed variables.

categories this is an order of magnitude higher than the impact of income, followed by a very large impact of floor area.

The next largest impact after SAP12 and floor area for households in energy poverty is whether there is gas heating, which reduces energy expenditure by £68.40/y. Next is whether it is a one-person household, which reduces space heating expenditure by £36.77/y for households in energy poverty compared to £15.65/y for low-income households not in energy poverty (Table 5) and by £47.15/y for very low-income households. For high/income households this is has the fourth largest impact, at approximately £56/y, behind having central heating, which reduces costs by approximately £9.70/y for high-income households and £10.80/y for very low-income households. An interesting result in Fig. 10, for low-income households not in energy poverty, is that the impact of a change in income on energy consumption is very small compared to the impact of the SAP12 rating – about one-tenth of that for households in energy poverty.

For all these we say “approximately” because the regression of non-transformed variables, given in Table 3, is subject to error due to the non-normality of the variables’ distributions. A re-transformation of the results to the actual values is also subject to error, because it only holds true at the mean value of the transformed variable (e.g. the mean of the logarithms of the space heating costs). In any case, these impacts are so low, compared to those of the SAP12 rating and the floor area, that they are hardly “significant” in the general meaning of this term.

We also note that the only variables which give p-values ≤ 0.1 for all income bands and categories are SAP12, floor area, and one-person household, while income after housing costs, tax and transfers also gives p-values ≤ 0 for low-income households both in and not in energy

Table 4
Regression of relevant variables against space heating costs, for the four income bands.

	Low income			High income			Very low income			Mid-low income		
Regressed against space heating cost	Coef.	t	p-value	Coef.	t	p-value	Coef.	t	p-value	Coef.	t	p-value
AHCIncome	0.00058	1.26	0.206	0.00157	10.750	0.000	−0.00117	−0.790	0.430	0.00075	0.790	0.428
FloorM2	3.87	41.38	0.000	4.18	41.49	0.000	3.65	20.16	0.000	3.98	36.45	0.000
SAP12	−19.93	−84.28	0.000	−21.74	−89.61	0.000	−19.45	−42.84	0.000	−20.15	−72.95	0.000
solid Wall Unins	1.96	0.38	0.700	12.31	2.10	0.036	6.79	0.70	0.486	−0.92	−0.15	0.877
gas Heating	−52.66	−6.79	0.000	−74.08	−8.65	0.000	−40.96	−2.64	0.008	−55.38	−6.20	0.000
central Heating	−9.70	−0.99	0.323	−25.45	−2.25	0.024	−10.80	−0.56	0.573	−12.15	−1.07	0.286
age16to24	−45.35	−4.37	0.000	−25.12	−1.29	0.196	−60.87	−3.71	0.000	−27.22	−1.94	0.052
working	−9.95	−2.20	0.028	−9.37	−1.75	0.080	−2.24	−0.24	0.807	−13.04	−2.50	0.012
sick Member	4.83	1.17	0.242	10.04	2.03	0.042	5.16	0.61	0.543	4.45	0.94	0.345
couple w. Dependents	−3.56	−0.69	0.491	39.68	6.34	0.000	−24.12	−2.19	0.029	4.05	0.70	0.486
one Person	−20.53	−4.32	0.000	−55.99	−10.17	0.000	−47.15	−5.10	0.000	−9.72	−1.74	0.082
private Rental	−14.32	−2.80	0.005	−51.20	−6.63	0.000	−27.71	−2.79	0.005	−8.42	−1.40	0.160
owner Occupier	18.06	3.21	0.001	−33.41	−5.13	0.000	15.25	1.20	0.232	17.32	2.76	0.006
_cons	1600.87	86.39	0.000	1711.56	89.24	0.000	1601.21	45.48	0.000	1605.73	66.91	0.000
F	0.000			0.000			0.000			0.000		
Adj R-Sq	0.745			0.715			0.715			0.758		
Observations	4884			7090			1384			3500		
highest VIF	2.12			2.05			2.32			2.06		

Table 5
Regression of relevant variables against space heating costs, for households in energy poverty by the LILEE indicator, and low-income households not in energy poverty.

	Households in energy poverty by LILEE indicator			Low income, not in energy poverty		
Regressed against space heating cost	Coef.	t	p-value	Coef.	t	p-value
AHCIncome	0.001843	1.7	0.089	0.000694	1.83	0.068
FloorM2	5.0435	25.76	0.000	2.991576	38	0.000
SAP12	−21.591	−40.91	0.000	−17.02066	−56.29	0.000
solid Wall Unins	7.5247	0.8	0.423	−5.125177	−1.06	0.290
gas Heating	−68.399	−4.26	0.000	−8.790812	−1.3	0.195
central Heating	−2.9467	−0.16	0.873	−48.76863	−5.32	0.000
age16to24	−56.621	−2.51	0.012	−34.63644	−4.07	0.000
working	−6.1906	−0.64	0.521	−11.5084	−3.05	0.002
sick Member	6.6706	0.75	0.454	5.682106	1.67	0.094
couple w. Dependents	4.0006	0.38	0.707	−9.142963	−2.08	0.038
one Person	−36.772	−3.47	0.001	−15.64551	−4.05	0.000
private Rental	−9.80122	−0.94	0.346	−16.17914	−3.62	0.000
owner Occupier	5.0218	0.43	0.671	30.77569	6.46	0.000
_cons	1602.8	43.64	0.000	1450.46	59.07	0.000
F	0			0		
Adj R-Sq	0.69			0.686		
Observations	1872			3012		
highest VIF	2.45			1.97		

poverty. We therefore focus mostly on these variables in the following summary discussion.

5. Discussion

An important finding is that although a change in income after housing costs and fiscal transfers (ANCIncome) makes relatively little impact on heating expenditure for households in general, its biggest impact is for households in energy poverty. For this reason we cannot dismiss it in a discussion of how to alleviate energy poverty.

Using the same database, Galvin [7] found that higher fiscal transfers to low-income households are highly unlikely to lead to substantial increases in energy consumption. This aligns with the findings of the study by Bagnoli and Bertoméu-Sánchez [72] who found that households receiving a social electricity tariff in Spain hardly increased their electricity consumption, even if they paid a lower rate. However, by categorising low-income households according to whether or not they are in energy poverty, we find a subtly different result. A change in income among households in energy poverty does make a significant difference to their energy expenditure, even though this is small.

Our findings therefore suggest that the current UK government approach of targeting energy policy with one-off payments like The Winter Fuel Payment, Warm Homes Discount and Cold Weather payments are at least partially effective. However, they may not relieve energy poverty as effectively as hoped, since the additional income is not necessarily all being spent on increasing thermal comfort. This might explain to some extent the ineffectiveness of several targeted energy poverty programs in reducing specific energy deprivation, as this can be partially attributed to the fact that some households use their additional funds to cover other essential needs [73,74]. But this does not mean that fiscal transfers to households in energy poverty are of no use. It more likely means that these households' most pressing priorities for spending have very little to do with heating. They may have to do with food, clothing, education, getting a better dwelling, medical needs [59] or paying off debt [62].

A second key finding is that in all cases the SAP12 rating – i.e. the energy efficiency of the dwelling – is by far the strongest determinant of space heating expenditure. Therefore, probably the most effective strategy for warming up the homes of households in energy poverty is to increase the energy performance of their dwellings. Each increase in SAP12 rating corresponds to a reduction in heating costs of around £20/y (see first histogram in Fig. 1). Therefore, for households in energy

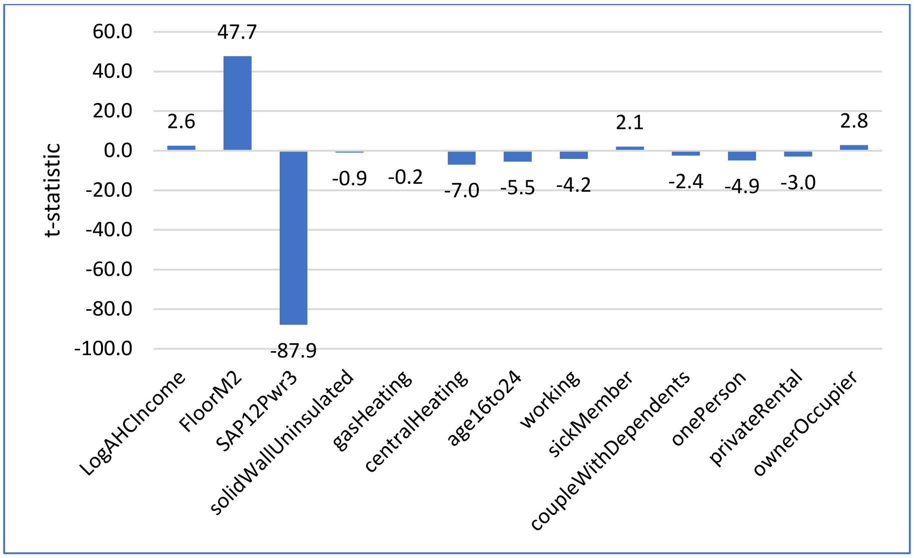

Fig. 5. T-statistics low-income households (<17,105) using variables transformed for normal distributions.

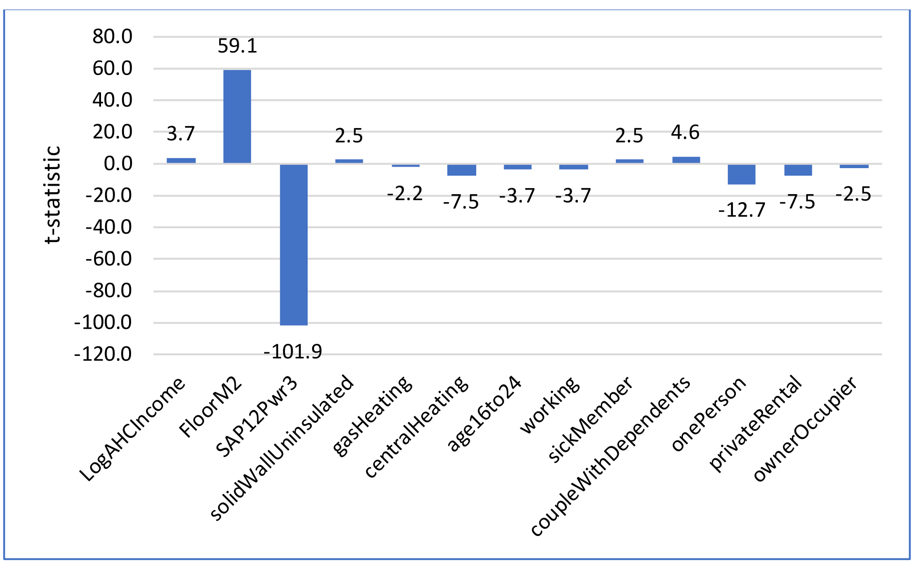

Fig. 6. T-statistics high income (≥17,105) using variables transformed for normal distributions.

poverty, with an average SAP12 rating of 59.48, increasing the SAP12 rating to the level of low-income households not in energy poverty, namely 71.45, could reduce space heating costs by about £240/y.

Although this may not help these households' finances as much as the direct monetary allowances outlined in Section 2, it will make a substantial, direct impact on cold, unhealthy homes. There needs to be extra focus on developing policies for the long-term solution of retrofitting energy-inefficient homes. This can provide enduring reductions in energy bills while also improving thermal comfort. This approach may also align better with the goal of reducing carbon emissions and tackling climate change.

This of course raises the further issues of how this would be paid for and whether it is economically viable, i.e., whether the reductions in energy use would pay for the renovations over the course of their technical lifetime, say 30 years – a topic currently being explored at length in Germany due to sharp increases in energy, finance and building costs [39]. A reduction in energy bills of £240/y only amounts to £7200 over a 30-year technical lifetime of the renovation measures, while a retrofit to increase the SAP12 rating from 59 to 71 will cost tens of thousands of pounds per dwelling. Sources of finance other than the household's reduced energy bills would need to be found. There are almost certainly co-benefits of energy efficiency and warmer homes, such as fewer sick days, longer lives and less strain on the health service [75–77]. Energy-efficiency upgrades therefore require financial support that is unlikely to come from direct energy savings. Schleich [11] investigated the adoption of energy efficient technologies by income categories in eight EU countries. He concluded that there are differences in retrofit measures implementation rates between the highest and lowest income quartile households and these differences would likely have been smaller with support schemes in place for lower income households, especially in the UK.

Without retrofit initiatives, energy poverty will persist in the UK, since for low-income households, immediate needs often take precedence over thermal comfort, even with rising incomes. Moreover, many live in properties owned by private landlords who lack the motivation to improve housing standards. Nevertheless, there are positive examples. The Scottish Landlord Register (https://www.landlordregistrationscotland.gov.uk/) requires all landlords to register and meet certain

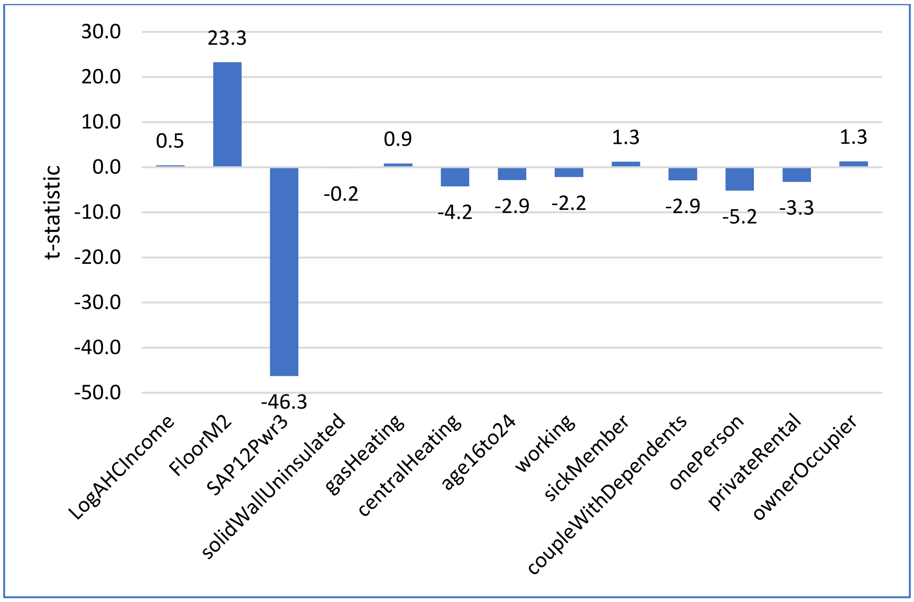

Fig. 7. T-statistics very low income (<9000) using variables transformed for normal distributions.

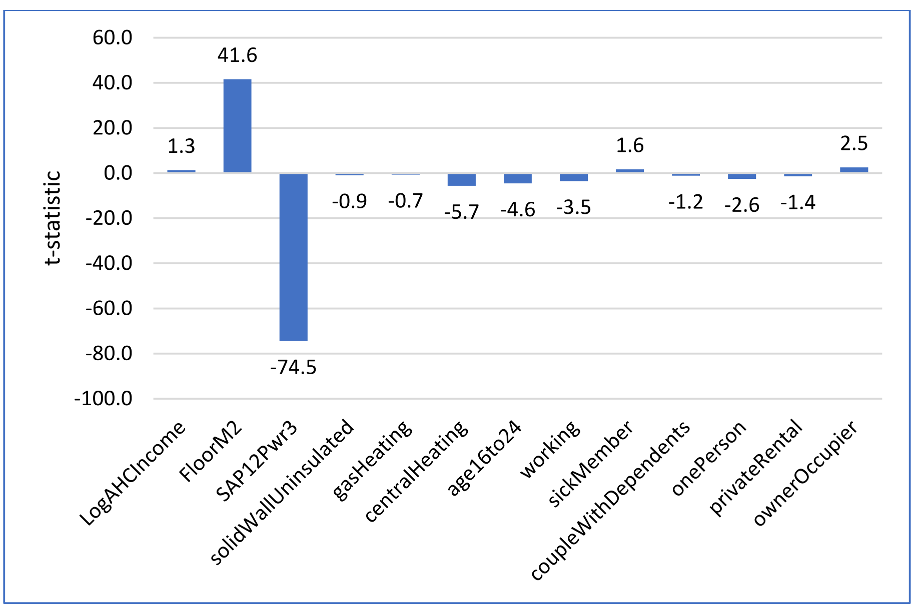

Fig. 8. T-statistics mid low income (9000 ≤ 17,105) using variables transformed for normal distributions.

standards. This helps to improve the standards of private renting by ensuring a property is fit to be let, though this is still far from ideal [78]. Some local authorities in Scotland offer specific ‘Good Landlord’ schemes aimed at encouraging best practices, offering advice, and sometimes financial incentives for improvements to properties. These schemes aim at enhancing tenant-landlord relationships, improving the quality of rental accommodation, and ensuring compliance with legal standards.

Another viable strategy would be constructing additional Council housing that is both energy-efficient and affordable. For instance, Cambridge City Council mandates that all newly constructed Council housing adheres to the Passivhaus standard. In this context, it is crucial to provide social housing providers with the necessary funding to accelerate a retrofitting strategy for households in need [79].

A third finding is that floor area makes a substantial difference to space heating energy costs, with about half to two-thirds the impact of SAP12 rating. On the one hand, this could suggest that low-income households are wise to live in dwellings that have the right size for their needs. On the other hand, this is not easy for older households whose dependants have left home and who find themselves with a large, older home that is very expensive to keep warm. Our analysis showed that for households in energy poverty, floor area has a much higher t-statistic in relation to other variables, than it does for other categories of households. This suggests that inability to downsize may be a significant driver of energy poverty.

A fourth and very interesting finding is that for all income groups, being a one-person household is associated with reduced energy expenditure, and for households in energy poverty the reduction is twice as large as for low-income households not in energy poverty. This needs more exploration because it might suggest that many one-person households are able to control their energy consumption more strategically than a multi-person household is able to. Note that other factors

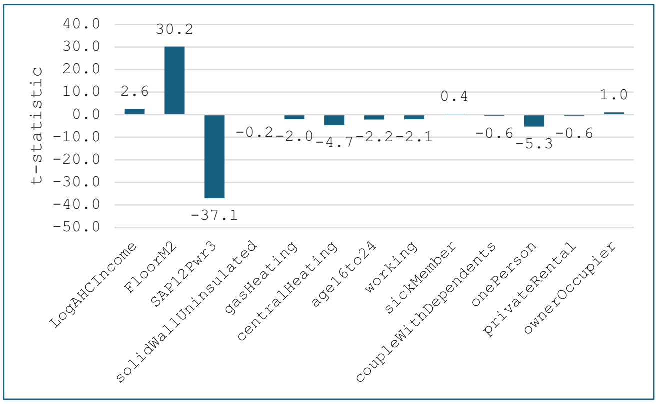

Fig. 9. T-statistics for households in energy poverty by LILEE indicator, using variables transformed for normal distributions.

such as floor area are controlled for by the regression method, so it is not just a case of low-income households living in smaller dwellings. Further research could survey one-person households to find out if they have skills and practices that could be transferred to multi-person households.

A fifth finding is that there are some variables that are statistically significant for some income bands and not for others, though the t-statistics show their impacts to be small. The main examples are:

- For high-income households, having uninsulated solid walls increases heating energy expenditure.
- For high-income households, having central heating reduces heating energy expenditure.
- For all households, having gas heating reduces heating energy expenditure (though heat pumps are not considered in the data).
- For low-income households of all categories, having a household head aged 16–24 reduces heating energy expenditure.
- For all except very low-income households and households in energy poverty, working (having a job) decreases heating energy expenditure.
- For high-income households, having a sick member increases heating energy expenditure.
- For high-income households, being a couple with dependants increases heating energy expenditure, but for a very low-income household this reduces heating energy expenditure.
- For most bands, being in a private rental dwelling reduces heating energy expenditure but for households in energy poverty no significant effect is evident.
- For high-income households, being an owner-occupier increases energy expenditure, but the opposite is the case for middle-low-income households.

Finally, an interesting issue for further detailed research: the household income figures in the database include all welfare transfers, and some of this, for some households, includes subsidies on energy bills (though this is very uneven throughout England). Therefore to some extent some households' energy consumption behaviour may be in part a response to a reduction in expenditure, rather than to an increase in direct income. A question for further research is, in the context of subsidies for energy costs, do low-income households respond differently to a reduction in expenditure, from how they respond to a direct increase in income.

6. Conclusions

This study contributes new knowledge in identifying which factors are associated with income and heating expenditure among low-income households in the UK, particularly those who are in energy poverty by the LILEE indicator. It takes household income as a starting point to understand heating demand in these households, while also comparing these with high-income households and with low-income households who are not in energy poverty. An important finding is that for low-income households who are not in energy poverty, a change in income (after housing costs and fiscal transfers) makes very little impact on heating expenditure and therefore, by implication, on heating practices. However, for households in energy poverty (who are also low-income) the impacts are significantly stronger, though still not large. This could be due to the priority given to other essential needs or expenses, and/or because these households have got used to under-heating and living in unhealthy conditions. It could also indicate that additional income is allocated mostly towards other necessities or savings rather than increasing heating consumption. In short, heating expenditure is relatively income-inelastic, and less so among households in energy poverty.

It is clear that for all income bands, by far the greatest impact on space heating expenses is the SAP12 rating. The advocacy for payment top-ups and a cash-first approach in policies is often rooted in the aim to provide immediate relief to low-income households facing energy

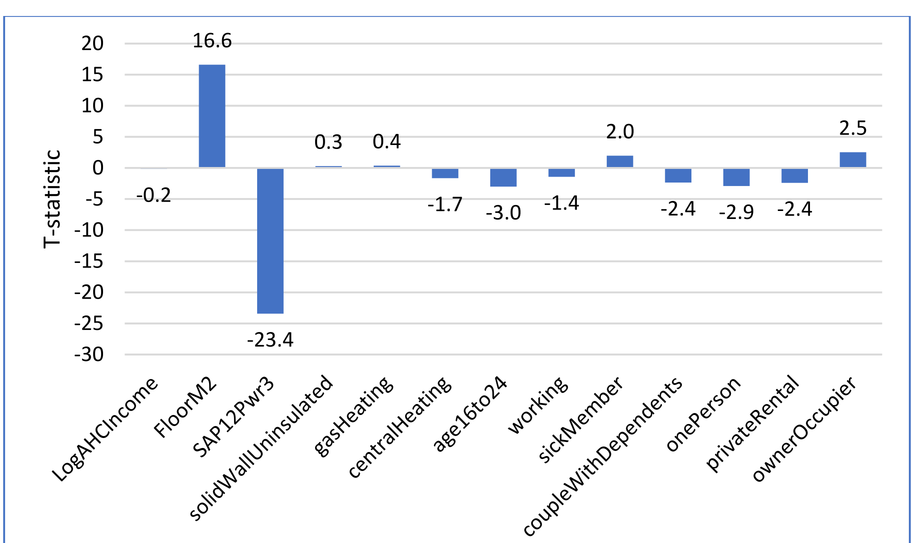

Fig. 10. T-statistics, income < 9000, households not in energy poverty by LILEE indicator, using variables transformed for normal distributions.

poverty. This is at least partially effective among households in energy poverty, and in any case it is very important to increase the income of low-income households. However, our findings suggest that the approach that will have the largest impact by far on energy cost reductions is to increase the dwellings' energy-efficiency: more specifically, to increase the SAP12 rating to at least 72. However, because this will result in reduced energy bills of only about £240/y, the energy-efficiency upgrade will not be paid for out of energy savings. This points to the need for targeted financial support for these upgrades. Society may well find these pay back through co-benefits of fewer days off work, longer lives and less strain on the health service.

Finally, this study argues for a holistic understanding of household economics when addressing energy poverty. As well as the technical inadequacy of many dwellings, energy poverty is rooted in poverty. Many UK households are at the nexus of energy and food poverty and are often in debt, including to friends and family. They do not have a liquidity buffer. Both poverty and technical energy efficiency issues need to be addressed persistently and universally. The study highlights the differential income inelasticity of energy expenditure and confirms that energy poverty indicators can effectively identify those in greatest need of support. However, while targeted support can alleviate some deprivation, the study argues that addressing both the root causes of poverty and technical energy efficiency issues is crucial for a holistic solution to energy poverty.

A limitation of the study is the volatility of energy prices in the years since the survey in 2019. The evolution of the price that households pay for energy has been complex since then due to a series of government interventions, but actual average prices are now around twice their mid-2019 level. Nevertheless, an advantage of this study is that it estimates micro-level changes in energy expenditure that are associated with micro-level changes in energy price, regardless of the absolute value of the price. It is highly unlikely that the ratios between t-statistics for the effect of energy price compared to SAP12 rating and floor area would be substantially different in a regime of higher energy prices.

CRediT authorship contribution statement

Ray Galvin: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Minna Sunikka-Blank:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Tijn Croon:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, 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.

Data availability

The authors do not have permission to share data.

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