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An econometric analysis of the drivers for residential heating consumption in the UK and Germany

Mounirah Bissiri [a, c, *], Inês F.G. Reis [a, c], Nuno Carvalho Figueiredo [a, c], Patrícia Pereira da Silva [a, b, c, d]

[a] Energy for Sustainability Initiative - University of Coimbra, Sustainable Energy Systems – MIT-P, Rua Sílvio Lima, Polo II, 3030-290, Coimbra, Portugal
[b] Faculty of Economics - University of Coimbra, Av. Dias da Silva, 165, 3004-512, Coimbra, Portugal
[c] INESC Coimbra, Rua Sílvio Lima, Polo II, 3030-290, Coimbra, Portugal
[d] CeBER, Centre for Business and Economic Research, Av. Dias da Silva, 165, 3004-512, Coimbra, Portugal

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ABSTRACT

Affecting millions of Europeans, energy poverty is increasingly high on the political agenda. This paper compares space and water heating demand at household level in Germany and in the United Kingdom (UK) between 1991 and 2015. The elasticities of consumption of space and water heating with respect to price, income and heating degree days (HDD) are examined using non-parametric models. Domestic heating consumption is highly elastic with HDD in both countries and HDD elasticities are found to be higher in the UK. From a certain income threshold, heating demand decreases as income increases in German households whereas demand rises with higher incomes in the UK. High price elasticities indicate that UK households are very responsive to energy conservation measures, therefore implying that a pricing policy will effectively reduce heating consumption. However, in Germany, the impact of pricing policies is unclear. Thus, the most effective policy measure to decrease domestic heating consumption in Germany in the long-run should be one which targets improvements of building envelope performance levels.

1. Introduction

In 2014, the European Union (EU) was the third biggest carbon dioxide (CO_2) emitter after China and the United States (U.S. EPA, 2017) with over one third of CO_2 emissions being attributable to the building sector. Buildings also represent 40% of the region's energy consumption (European Commission, 2018), of which 63% is for residential use (Balaras et al., 2007). At household level, space and water heating accounted for over 80% between 2000 and 2015 (Odyssee-Mure, 2017). The sector is characterized by aging and energy inefficient building infrastructure with a negligible share of renovated buildings (European Commission, 2018). There is a huge potential for CO_2 emissions and energy consumption reductions through the promotion of energy efficiency of the building stock (Labanca et al., 2015; Ma et al., 2018). This in turn, can considerably reduce the incidence of energy poverty which is already at the heart of the European political agenda as one of the main issues to be considered in the implementation of future energy scenarios. In a context of energy poverty in developed countries, the energy service which is the easiest to discard is space and water heating, thus putting a strain on home comfort. Indeed, for these countries, there are three main drivers of energy poverty, namely energy prices, income and housing energy efficiency (Department of Energy and Climate Change, 2015). Households in a situation of energy poverty generally have two options: invest a high share of their incomes on energy services, hence compromising the amount of money that they are able to invest in other basic needs (such as food and transport) or sacrifice their - well-being by living in cold and uncomfortable dwellings (Thomson et al., 2016). In other settings such as China and developing countries, energy poverty exists in a different form through the lack of access to basic energy needs and the traditional, unsustainable use of biomass resources for cooking purposes (Wang et al., 2015). Therefore, even though China tops the world's largest CO_2 emitters, energy poverty as it occurs, may be seen as distinct from the developed nations.

* Corresponding author. Energy for Sustainability Initiative - University of Coimbra, Sustainable Energy Systems – MIT-P, Rua Sílvio Lima, Polo II, 3030-290, Coimbra, Portugal.
E-mail address: mounibiss@gmail.com (M. Bissiri).

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In the current context of energy use reduction and the decarbonization of energy supply and demand, exacerbated by the risk of poverty on vulnerable consumers, it is paramount to be able to recognize and interpret the drivers for consumption. In recent years, a large number of academic studies have used various techniques to estimate elasticities of demand, from parametric models using linear, log-linear and dynamic relationships to non-parametric models. In every country, the driver for energy consumption is the demand for energy services, namely lighting, the use of electrical appliances, transport, and water and space heating or cooling, rather than primary energy sources such as electricity, natural gas, biomass and oil (Fouquet and Pearson, 2012). Yet, most of the literature on elasticities of demand has focused on the prices of final energy sources instead of the services they provide, and/or on incomes, hence disregarding any external variables associated with weather conditions, for example, which may lead to consumer short-term adjustment. Moreover, in some cases, income and price elasticities are estimated using time series energy data with no account for efficiency improvements (Kouris, 1983). It has been argued that putting emphasis on energy instead of energy services will be conducive to spurious evaluation of consumer responses to variations in income, changing prices and efficiency improvements (Fouquet and Pearson, 2012). Table A1 reports a selection of studies estimating income and price elasticities of demand for energy or energy services at the global level. This paper seeks to contribute to the existing knowledge and to help to design better energy poverty mitigation policies in developed countries by showing how domestic end-users adapt their space and water heating consumption according to key household variables such as incomes and heating prices alongside an external parameter, heating degree days (HDD), encapsulating weather conditions. It also elaborates on the responsiveness of households to energy efficiency measures. For this purpose, case studies of two of the leading EU economies, namely the UK and Germany, are considered. The novelty of this study is two-fold: (1) As noted in Lim et al. (2014), HDD should be a key variable to include in such econometric models, and to the best of our knowledge, this is the first time that the influence of HDD is studied alongside variations of income and energy service price in order to assess the corresponding elasticities in the domestic heating sector; (2) The income variable used is in the form of median equivalized household disposable incomes (MEHDI) to better capture the living conditions of a typical household rather than the traditional Gross Domestic Product (GDP) per capita values which in fact, represent the national standard of living.

Until very recently, the number of people who could suffer a given form of poverty was not considered relevant within the EU and few related studies focus on Northern and Western European countries. So far, the UK has been one of the few countries to provide an official definition to this concept according to the fraction of income spent to maintain adequate levels of household thermal comfort (Daly and Walton, 2017; EPEE, 2015) and it was the first and one of the few EU states to give voice to this issue, bringing it into the political agenda (Bouzarovski, 2014). As of 2016, UK and Germany held the largest shares of greenhouse gas (GHG) emissions in the EU with 11.6% and 21.1%, respectively (Eurostat, 2018). Emissions reductions have been significant in the industrial and commercial sectors but not in the residential sector which still holds an untapped savings potential (Labanca et al., 2015). However, following the Paris agreement, the Climate Action Plan 2050 of the German Government makes provision for 66–67% of reduction in GHG emissions from the buildings sector by 2030 compared to 1990 levels, the highest sectoral target (BMUB, 2016). In the UK, the Committee on Climate Change has urged the Government to consider more stringent measures to meet their national climate commitments (Committee on Climate Change, 2018). Achieving these targets may have positive impacts in terms of housing affordability and comfort for the current 3.2 million of Germans and 3.8 million UK residents unable to keep their homes adequately warm (EU Energy Poverty Observatory, 2019). Hence, on an individual basis, these countries provide relevant case studies to meet the objective of this study. The reasoning behind using them for a comparative analysis lies in the fact that although sharing a common feature of strong economies and comparable heating demands, their energy sectors differ in many points with contrasting heating consumption levels, energy prices and energy sources for domestic heating.

Therefore, a quantitative analysis of consumption, incomes, HDD and domestic heating prices time series data, using an econometric model, is performed to determine corresponding elasticities. These elasticities translate the extent to which end-users are willing to refrain from guaranteeing thermal comfort in their homes based on prices, incomes and short-term weather variations. Time series estimates of elasticities were shown to provide sound results which can suitably inform planning processes (Kouris, 1983).

This paper is organized into four sections. Section 1 introduces the issue and reviews the existing literature on estimates of elasticities of heating and/or energy demand. Section 2 covers the econometric model and the data used to calculate our own estimates. In Section 3 we present and discuss the empirical results of the model, and the last section concludes and provides policy recommendations.

2. Materials and methods

2.1. Case study

Despite being two of the biggest European economies, the problem of energy poverty is still a current and relevant issue in both Germany and the UK. Fig. 1 shows the average percentage of households at risk of suffering from energy poverty between 2005 and 2016 in the UK and Germany (the figure for the share of UK households in arrears on utility bills in 2009 is unreliable according to Eurostat, therefore, an interpolated value was plotted). While the differences between the shares of households unable to keep their homes adequately warm are not very significant between 2006 and 2009, they become more relevant since 2010, with a worsening of the situation in the UK. This issue is compounded by an additional high share of UK households with arrears on their utility bills. More severe weather conditions (translated by the increase in the number of HDD) and rising energy prices may have led to a higher incidence of this problem in both countries in the period 2011–2015. However, in the past few years, the share of German and UK households suffering from energy poverty has been reaching lower levels.

As previously mentioned, there are three main drivers to classify a household as energy poor, namely household income, energy requirements and fuel prices. The influence of these three dimensions was exploited in the context of this work and will be further addressed.

2.1.1. Energy requirements

Both in the UK and in Germany, the residential sector holds the largest proportion of buildings (EU Building Stock Observatory, 2015), and space and water heating represents around 80% of the total residential energy consumption (see Fig. 2 and Fig. 3 where Mtoe stands for million tons of oil equivalent). Space and water heating services can be seen as a proxy to the existing dwellings' thermal comfort conditions. Heating consumption is included in the model through the space and water heating consumption

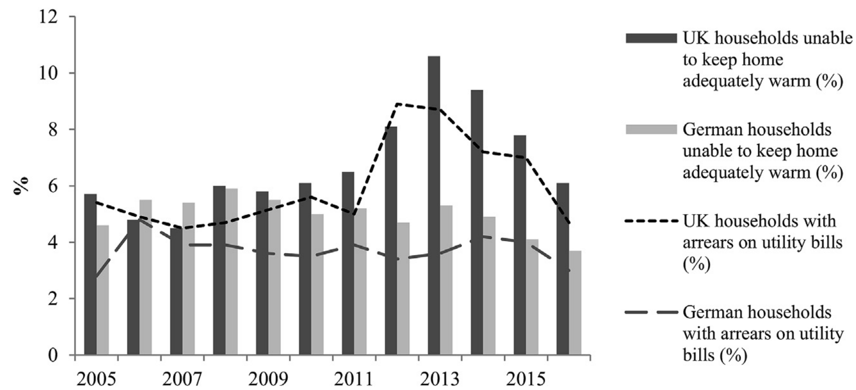


Fig. 1. Average percentage of households at risk of suffering from energy poverty between 2005 and 2016 (Authors, from (Eurostat, 2017a, 2017b)).

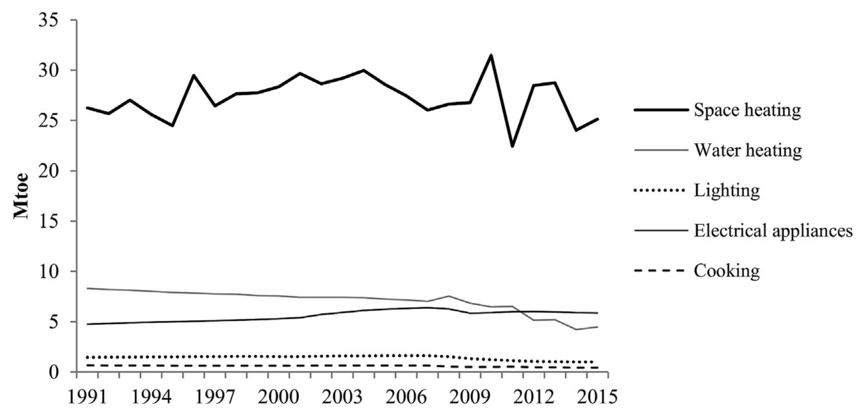


Fig. 2. Average consumption of energy services in the UK in Mtoe, 1991–2015 (Authors, from Odyssee-Mure, 2017).

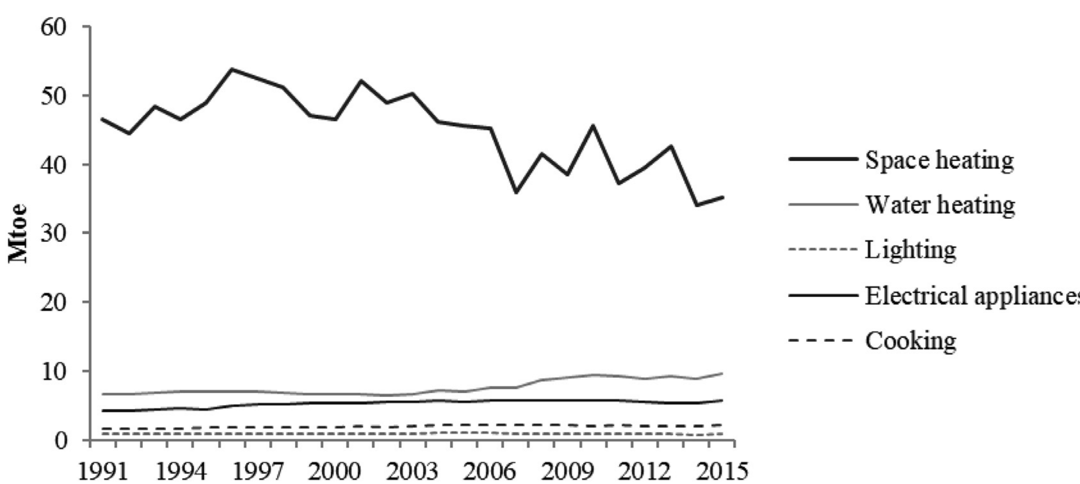


Fig. 3. Average consumption of energy services in Germany in Mtoe, 1991–2015 (Authors, from Odyssee-Mure, 2017).

variable, represented as E_t.

High space and water heating energy consumption levels may translate inefficient buildings stock thermal properties or very inefficient heating technologies. Regarding the building stock quality, German residential envelopes and components have lower heat transfer coefficients (U-values are energy efficiency indicators in buildings) compared to the UK ones, indicating a higher energy performance of the German housing stock. Indeed, in 2012, the German average U-value of the residential building envelope was 1.16 W/m^2.°C, a value almost three times as low as in the UK (3.15 W/m^2.°C) and slightly lower than the 2014 EU-28 average (1.69 W/m^2.°C) (EU Building Stock Observatory, 2015). Despite the best conditions in terms of buildings thermal conditions, Germany performs the worst in the technologies used for space and water heating, since oil and gas-fired equipment are still the most common while gas-fired technologies are installed in the majority of UK households. Buildings and heating technologies efficiencies are merged in the heating demand which is, in turn, deeply dependent on external weather conditions, Thus, to exploit how short-term temperature changes may influence the levels of responsiveness to income or service price changes, an HDD variable was introduced in the model as W_t. This variable is a measure of how cold the temperature is in a period and it may be used to assess heating needs (U.S. EIA, 2018).

Using UK and Germany as case studies and following the "*ability to keep the house adequately warm*" index, heating needs were considered more relevant than cooling needs, hence the HDD variable was included in the analysis. However, in countries with warmer weather conditions it may be more appropriate to determine the cooling conditions (using the cooling-degree days variable). Situations may also occur where the inclusion of both variables is appropriate.

2.1.2. Household income

Income is a common factor influencing the demand of all kinds of goods and energy is no exception. A high-income consumer is less affected by goods prices, so the demand is also less affected. On the other hand, goods demand from lower income consumers would be highly sensitive to price changes. Thus, assessing how income influences the domestic heating demand in two countries with similar income levels but so distinctive heating prices are relevant steps forward. To exploit income influence on heating demand and unlike several other studies (Bakhat et al., 2017; Fouquet, 2016; Jamil and Ahmad, 2011; Lim et al., 2014), median equivalized household disposable incomes (MEHDI) rather than GDP per capita figures were employed. According to Stiglitz et al. (2009), GDP values reflect a country's standard of living but fail to capture the actual well-being of households, while MEHDI are more representative of households' well-being and should be used instead of GDP per capita when analyzing household settings, as argued by Deaton (2003) and Atkinson et al. (2015). The income variable is represented in the model as Y_t.

In light of Fouquet (2016), UK consumers, who have generally lower disposable incomes in comparison with German consumers, should be more responsive to changes in income. Therefore, although enjoying relatively high disposable incomes and lower energy prices, the amount of money that UK households have to spend to guarantee adequate thermal conditions in their homes is relatively high.

2.1.3. Fuel price

Similarly, price is also an important variable affecting demand, but has a different nature since it depends on the good/service demanded itself. Energy is understood by users as an essential good so, even with incremental price increases, demand does not decrease immediately. However, when price rises such that it compromises more vital goods (such as food), energy demand is affected and "less important" services such as domestic heating are neglected. Heating technologies used in both countries are different as well as the fuel prices. For both countries, electricity, gas and oil prices were included since those fuel sources were the most widely used for space and water heating (Fig. 4 and Fig. 5). In both countries, gas is the most used fuel, but in Germany the share of oil-fueled heating technologies is still quite high, establishing a great opportunity for improvement with the replacement of these technologies for electricity or gas-fueled ones.

Since housing efficiency is a key element accounting for energy poverty, it is relevant to understand how the implementation of energy efficiency measures at household level is influenced by the responsiveness to changes in energy service price (included in the model as the P_t variable). Alberini and Filippini (2011) argue that high price elasticities can be associated with high consumer responsiveness to energy conservation measures. Hence, it would be expected that price elasticities of domestic heating consumption in Germany have lower values than in the UK. Therefore, German consumers would be less concerned over changes in the price of a service that provides thermal comfort given the more efficient structural features of housing stock allowing for reduced levels of discomfort.

2.2. Data

Energy demand varies from country to country depending on GDP, industrial and technological development, geographic location, population lifestyles and energy prices (Phoumin and Kimura, 2014). With the deregulation of the energy market, consumers may be exposed to greater price volatility (Fan and Hyndman, 2011). Thus, in order to guide the design of more efficient energy policies, forecasting how energy consumers react to changes in price, income and other related variables is of the utmost importance and in this context, elasticity estimates can provide information about consumer behavior (Madlener et al., 2011). Studies using macro-economic data play a relevant role given their reliability and high level of coverage, but are limited by the generalization of the variables since lack of data generally prevents a more disaggregated analysis (Silva et al., 2017). An empirical analysis of the relationships between domestic heating consumption, HDD and two macro-economic variables, namely median equivalized household disposable incomes and heating prices in the UK and Germany was carried out using yearly data for the period 1991–2015. The choice of the period was driven by data availability. Table 1 presents the main variables included in the econometric model, as well as the criteria and assumptions used for calculation purposes.

Fig. 6 displays domestic heating consumption, median equivalized disposable incomes, HDD, and energy and heating prices in the UK and Germany between 1991 and 2015. Gas has been the most used heating source in UK households, and electricity is not significant in the total fuel use in Germany for the study period. Hence, for the sake of clarity, UK electricity and oil prices as well as German electricity prices are not represented in Fig. 6 (d).

Although both countries enjoy high disposable incomes, heating price in the UK is considerably lower compared to Germany, which heating price is largely inflated by oil and gas prices. However, the amount of money that UK households have to spend to guarantee adequate thermal conditions in their homes is relatively high, due to the bad housing situation. Furthermore, HDD tend to follow the same patterns in both countries, even though they are slightly lower in the UK.

2.3. Econometric model

Elasticities of energy demand can be estimated using parametric or non-parametric models. Parametric models assume functional forms in the data generation process, which can cause misspecifications (Karimu and Brännlund, 2013). This was confirmed for our data samples when attempting the use of VECM and cointegration methods, which have been applied previously across the literature to evaluate different policy issues, for instance, the effects of weather conditions on renewable energy prices, the impact of carbon prices on electricity stock market values and electricity prices, and electricity market integration (Bunn and Gianfreda, 2010; Pereira da Silva et al., 2016; Figueiredo et al., 2016a,b; Freitas and Silva, 2013). Some applications of non-parametric models were seen in the literature, such as, to estimate elasticities of energy demand and analyze spot electricity markets in Europe (Figueiredo et al., 2015, 2016; Karimu and Brännlund, 2013). Given that non-parametric models do not rely on previously assumed functional forms, we have opted to employ this type of

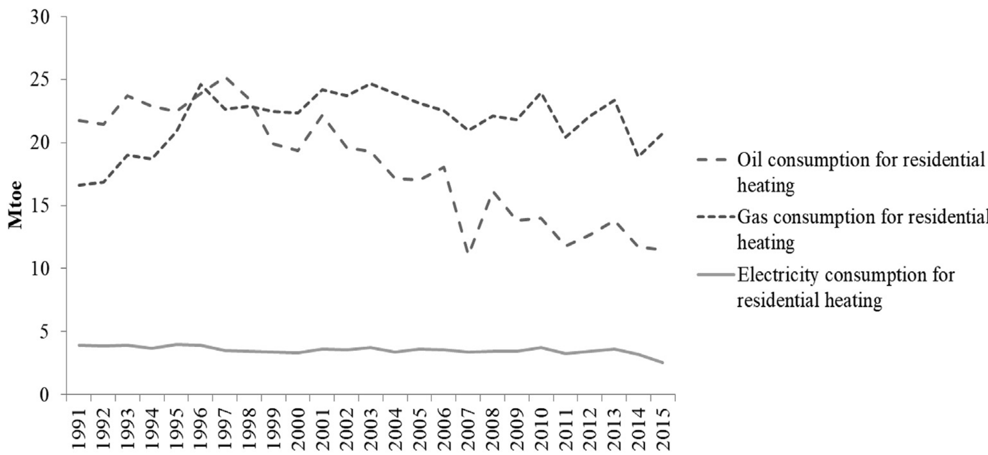


Fig. 4. Fuels used for heating purposes in Germany in Mtoe, 1991–2015 (Authors, from Odyssee-Mure, 2017).

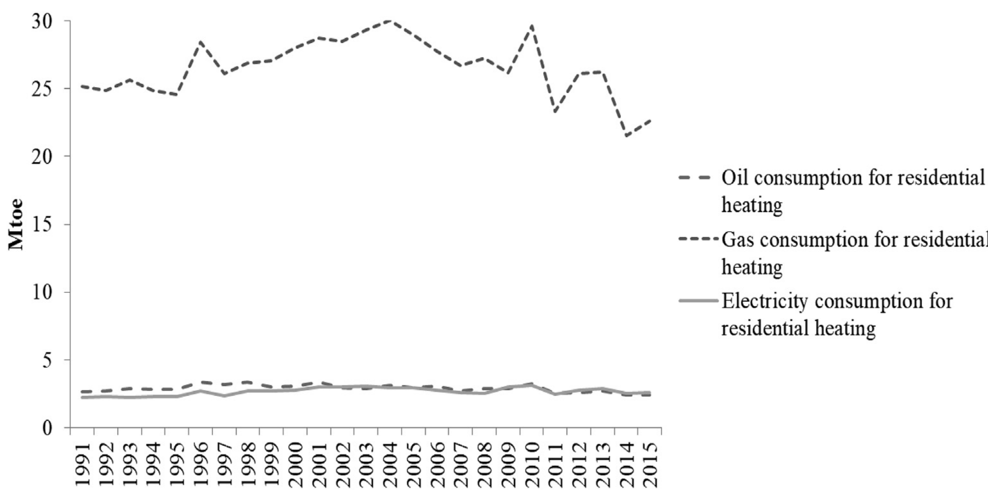


Fig. 5. Fuels used for heating purposes in the UK in Mtoe, 1991–2015 (Authors, from Odyssee-Mure, 2017).

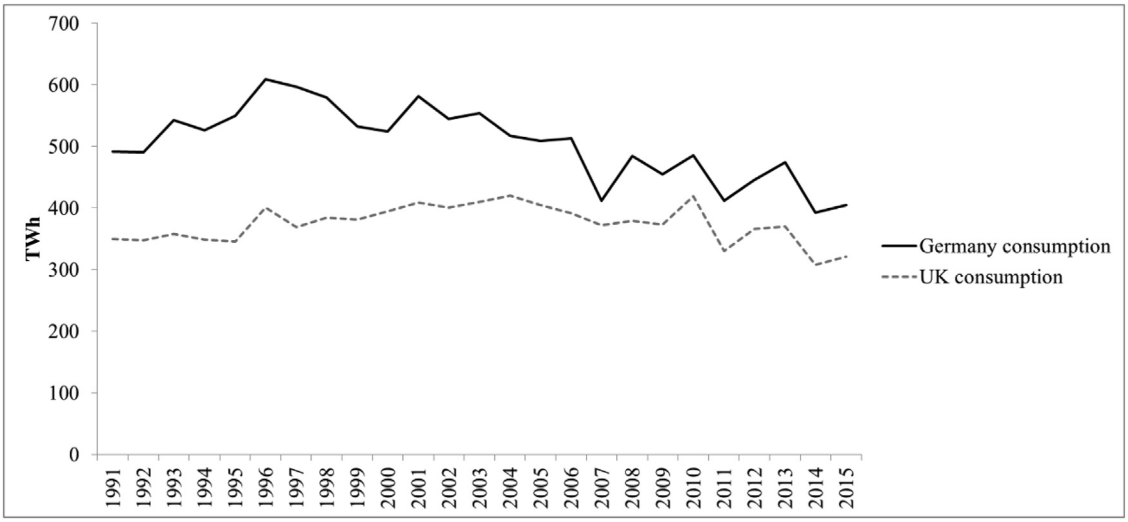
Table 1
Variables definition and criteria presentation.

Main variables	Criteria and assumption for calculations	Data source
Space and water heating consumption (E_t)	Used as proxy for energy poverty.	Odyssee-Mure database
Heating degree days (HDD) (W_t)	HDD were introduced to exploit how short-term temperature changes may influence the levels of responsiveness to income or service price changes.	Eurostat database
Median equivalized household disposable incomes (MEHDI) (Y_t)	MEHDI values rather than GDP per capita figures were employed.	Eurostat database
Heating prices (P_t)	The average heating price for each year was calculated by multiplying the corresponding energy price by the efficiency of the heating energy service, as suggested in (Fouquet and Pearson, 2012). Data on domestic heating efficiencies for both countries was retrieved from Odyssee-Mure database where they are referred to as ODEX[a] factors. Annual energy prices were approximated to weighted averages according to the annual share of domestic consumption of electricity, gas and oil. Domestic heating prices were then obtained by multiplying annual weighted averages of energy prices by annual ODEX values.	Eurostat database; Statista database and UK Government's website

[a] ODEX is the index used in the ODYSSEE-MURE project to measure the energy efficiency progress by main sector and represents "*a better proxy for assessing energy efficiency trends at an aggregated level than the traditional energy intensities, as they are cleaned from structural changes and from other factors not related to energy efficiency*" (Odyssee-Mure, 2017).

models, through the use of the 'np' package in R (Hayfield and Racine, 2008).

Previous studies on energy product and service demand (Fouquet and Pearson, 2012; Lim et al., 2014) used the Cobb-Douglas demand function to analyze the consumption of space and water heating. To this energy demand function, HDD is introduced as an additional factor (Eq. (1)). Through a logarithmic transformation of this equation the energy service demand function is written as in Eq. (2). Therefore,



(a)

(b)

Fig. 6. (a) Domestic heating consumption; (b) MEHDI; (c) HDD and (d) Energy prices in the UK and Germany (1991–2015) (Authors, from Odyssee-Mure, 2017; Eurostat, 2017c)

$$E_t = A(P_t)^{\alpha_1}(Y_t)^{\alpha_2}(W_t)^{\alpha_3} \quad (1)$$

where the subscript t represents time; E_t is the energy service consumption; P_t is the price of energy service; Y_t is the real income; and W_t is the HDD.

$$E_t = \alpha_0 + \alpha_1 P_t + \alpha_2 Y_t + \alpha_3 W_t + u_t \quad (2)$$

where α_0 replaces ln A; P_t, Y_t and W_t are the price, real income and HDD logarithms; and u_t is a forecast error term for different time periods.

The non-parametric model then assumes the following form:

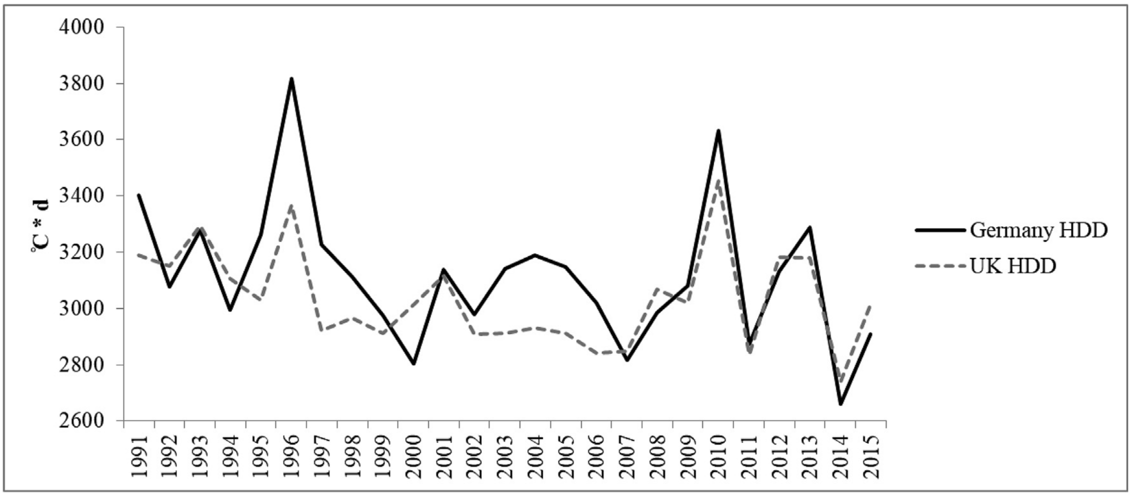
$$E_t = g(P_t, Y_t, W_t) + u_t$$

where $g(\cdot)$ is the non-parametric estimator of unknown functional form (Li and Racine, 2007).

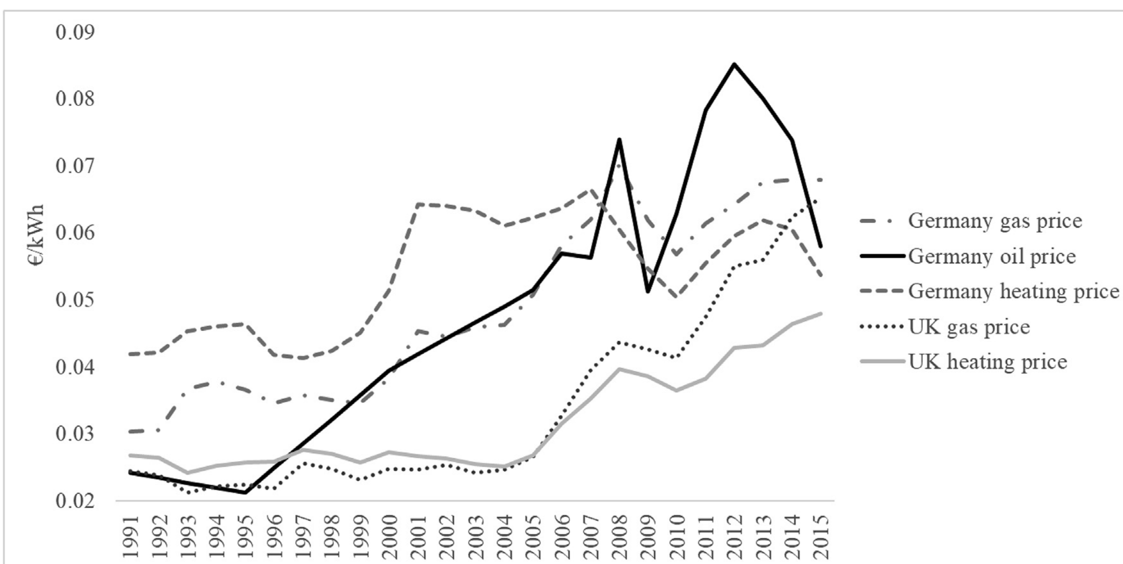
The local constant estimator $\widehat{g}(\cdot)$ is then given by:

$$\widehat{g}(P_t, Y_t, W_t) = \frac{\sum_{t=1}^{n} E_t \cdot K\left(\frac{P_t - p}{h_p}\right) \cdot K\left(\frac{Y_t - y}{h_y}\right) \cdot K\left(\frac{W_t - w}{h_w}\right)}{\sum_{t=1}^{n} K\left(\frac{P_t - p}{h_p}\right) \cdot K\left(\frac{Y_t - y}{h_y}\right) \cdot K\left(\frac{W_t - w}{h_w}\right)}$$

where h are the selected bandwidths according with the Kullback-Leibler cross-validation (Hurvich et al., 1998; Racine, 2007), $K(\cdot)$



(c)



(d)

Fig. 6. (*continued*).

the Gaussian kernel (Hayfield and Racine, 2013).

3. Results and discussion

Table 2 summarizes the p-values, and the minimum, maximum, median and mean elasticities of each variable P, Y and W for both countries. The variables P, Y and W respectively represent heating price, median equivalized disposable income and HDD. The elasticities of P, Y, W with respect to domestic heating consumption represent the values observed over the sampled time period. Hence, the minimum or maximum elasticity of any given variable is the lowest or highest elasticity observed for the variable between

Table 2
Results of non-parametric tests.

	Variable	p-values	Min. elasticity	Median elasticity	Mean elasticity	Max. elasticity
UK	P	($<2.22\ e^{-16}$)***	−0.4355	−0.3269	−0.2452	0.6960
	Y	($<2.22\ e^{-16}$)***	−0.3624	0.2162	0.1889	0.3898
	W	($<2.22\ e^{-16}$)***	−0.5599	0.7431	0.5543	1.1393
Germany	P	(0.216)	−0.6130	0.0164	−0.1448	0.1132
	Y	(0.004)**	−0.8840	−0.5917	−0.3385	0.7046
	W	(0.015)*	0.2631	0.5319	0.4735	0.5831

0.1% significance level; **1% significance level; *5% significance level.

1991 and 2015. The mean elasticities denote the averages of the corresponding elasticities during the sample period. The mean income elasticity, for example, provides a sense of how domestic heating consumption changes on average for a 10% rise in income. This percentage of change is only valid for the study period 1991–2015. All elasticities are found to be significant at least at the 5% level except for heating price in Germany which is not statistically significant. The significance levels were established through bootstrapping with independent identically distributed draws in the non-parametric model. Graphical representations of these elasticities are shown in Fig. 7, Fig. 8 and Fig. 9. It is to note that the comparative analysis between UK and Germany is made for each individual variable P, Y and W. No pairwise or three-fold-wise comparison following an optimization process is performed as doing so would go beyond the scope of this study. Notwithstanding, it is possible to give an interpretation to the meaning of the elasticity values of each variable against the background of the other two variables from a chronological perspective, as will be done in the following paragraphs of this section.

All UK variables are found to be significant at any level and the signs associated with the elasticities are coherent with economic theory i.e., price elasticities are negative, and both income and HDD elasticities are positive as expected. Negative values mean that heating consumption and heating prices evolve in opposite directions whereas positive values of income, for instance, suggest that as income increases heating consumption also rises. However, maximum price elasticity, minimum HDD elasticity and minimum income elasticity do not have the expected signs. The positive value of the maximum price elasticity may be explained by the fact that regardless of the price of domestic heating, consumption does not decrease accordingly due to high HDD values. In these exceptional cases, heating demand would in fact increase by around 7% for a 10% rise in prices in order to guarantee a certain level of comfort in homes. Historically, this maximum value corresponds to the period 2000–2001 when heating prices reached their highest level since 1997 and coincides with the third HDD peak from 1991. As for the

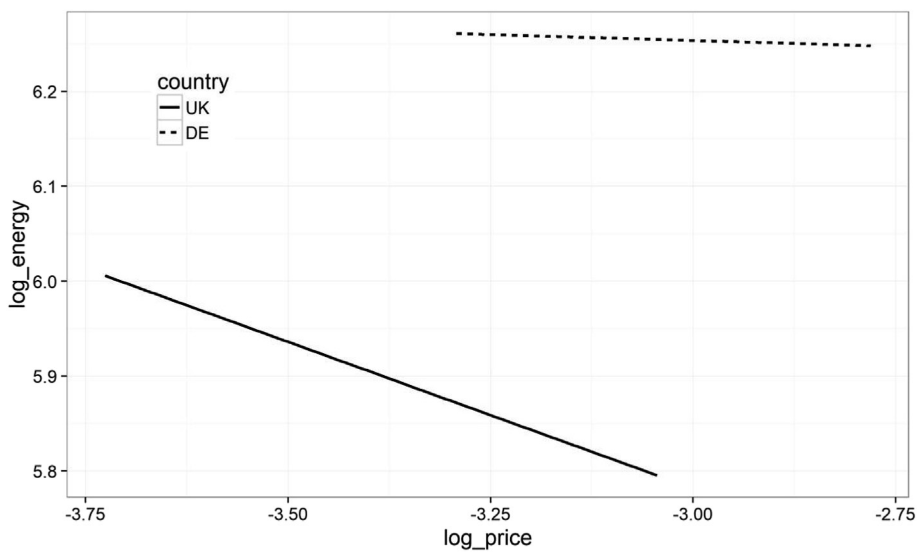


Fig. 7. Domestic heating consumption as a function of price in the UK and Germany.

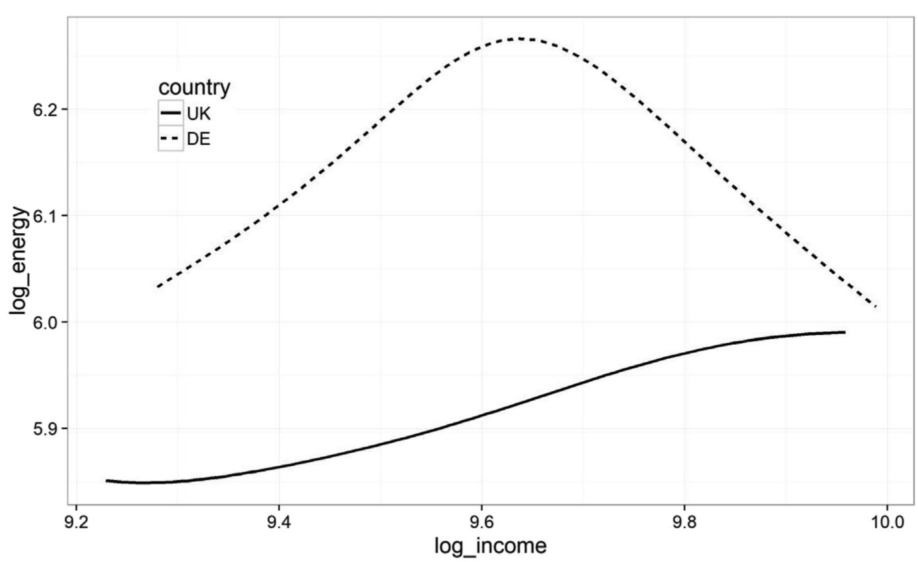


Fig. 8. Domestic heating consumption as a function of income in the UK and Germany.

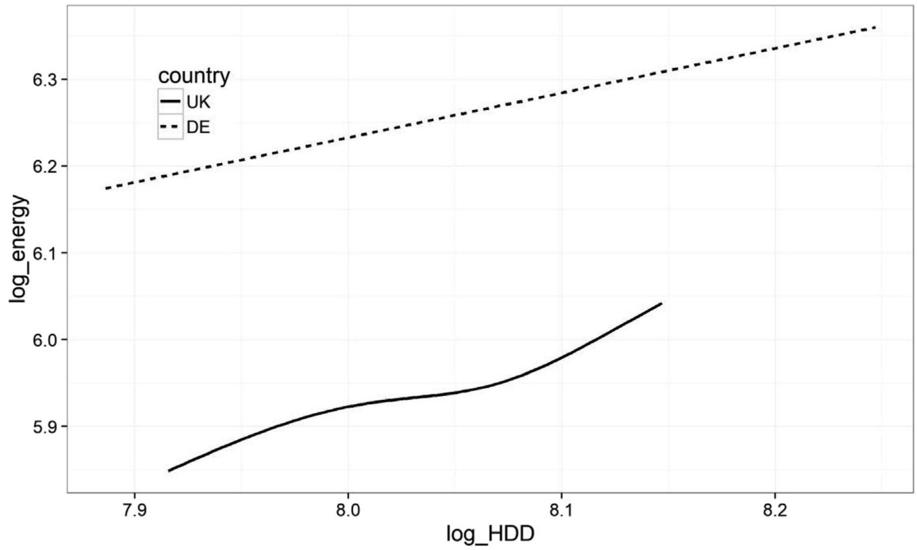


Fig. 9. Domestic heating consumption as a function of HDD in the UK and Germany.

minimum income elasticity, it suggests that a 10% increase in disposable incomes results in 3.6% consumption reduction and corresponds to the period 1994–1995 which was characterized by a 12–19% income fall, lower heating prices and lower HDD values compared to 1991-levels. The minimum HDD elasticity of −0.5599 corresponds to the same time period as the minimum income elasticity.

For Germany, price elasticities are found to be insignificant while income and HDD elasticities are significant at the 5% level. Moreover, economic theory is satisfied across all values for HDD elasticities but only for the maximum income elasticity value. Negative income values in Germany suggest that although it would be expected that consumption rises with disposable incomes in any setting, this is not the case for German households, probably owing to more efficient dwellings in higher income households. A closer look at the positive value for maximum income elasticity shows that it corresponds to the period 2014–2015 when heating prices dropped significantly to reach their lowest levels since the global financial crisis, especially for oil-fueled heating systems. At the same time, disposable incomes rose exponentially but HDD levels were not exceptionally high. It may, therefore, be assumed that the combination of low prices and high incomes led to an overall rise in heating consumption even in more energy efficient dwellings with extended heating times or slightly higher thermostats to increase home comfort, for instance. The same type of conclusions regarding maximum and minimum HDD elasticity values can be drawn. The maximum HDD elasticity value was observed in 1996, coinciding with the highest HDD peak and lower heating prices compared with previous years. The minimum HDD elasticity may have been recorded during a less rigorous winter in 2011, relatively low heating prices and rising disposable incomes. An analysis of the mean elasticity values shows that a 10% increase in income represents a 4% reduction in heating consumption. At first glance this result seems inappropriate since it would be expected that an increase in the available domestic income should translate into an increase in the standards of dwellings thermal comfort and therefore, in the increase of the heating consumption. However, this result can also be interpreted through the efficiency lens, i.e. this apparent contradiction may mean that with an increase in household income, consumers adopt more efficient technologies or invest in high performance buildings which inevitably impacts the heating needs. Further study would be necessary to ascertain the validity of this assumption. As for the HDD elasticity result, as expected, an increase in HDD, associated with a worsening of external weather conditions, would represent an increase in heating demand.

For the sake of having a more accurate picture of the typical behavior of households with respect to each of the three variables, it appears more adequate to consider mean values in the comparative analysis. The comparisons would still hold if the median values were used even though they are slightly higher in absolute terms. Since the p-value of the price variable for Germany is not statistically significant, no interpretation of the price elasticity can be made for this sample and no objective comparison with the UK can be done. It can only be concluded that with a low mean price elasticity of −0.2452, meaning that for a 10% increase in heating price, consumption would fall by 2.5%, UK households are mildly responsive to changes in heating prices. On the contrary, the mean HDD elasticity shows that for high mean HDD elasticities in both countries indicate that 10% increase in HDD values yield around 50% increase in domestic heating consumption. With a mean HDD elasticity of 0.4735 in Germany, which is lower than the mean UK HDD elasticity of 0.5543, German households show a lower level of response to HDD variations. This means that for each percentage increase in HDD, heating demand increases at a lower rate compared with UK households. These HDD elasticities may come as tangible evidence of the higher building performance in the German residential sector allowing for reduced response to short-term temperature variations.

The most striking difference between the two residential sectors lies in the mean income elasticity values as well as the income elasticities plots despite displaying comparable income ranges over the studied time period. Indeed, contrasting patterns of income elasticities as shown in Fig. 8 reveal dissimilar responses of heating consumption in relation to changes in incomes. A low mean income elasticity of 0.1889 denotes that UK households only slightly change their heating consumption in response to income variations. In contrast, the mean income elasticity in Germany is strictly negative and higher in absolute value than that of the UK. While a negative value of income elasticity may appear uncoherent with economic theory, it seems plausible when housing stock performance is fully accounted for. Furthermore, variations of income elasticities over the sampling period show increasingly positive values until an annual disposable income of around €14,620 to €14,915 after which a descending trend is observed. Thus, the wealthier a German household is the lower their heating consumption, most probably owing to higher investment in more efficient housing equipment.

On the whole, both UK and German households which are sitting in cold climate zones, are understandably highly sensitive to HDD values. This implies that with high HDD values, a notable rise in domestic heating consumption is observed to keep homes adequately warm. Also, even though holding similar median equivalized disposable incomes, it is seen that the disposable income levels have a higher impact on heating consumption in Germany. Consumption increases with income for households at the lower end of the income spectrum and decreases as the higher end of the spectrum is reached.

As described in Table A1, estimates of income and price elasticities of domestic heating consumption in UK and Germany have mainly been studied by Fouquet (2016), Schulte and Heindl (2017) and Tovar-Reanos and Wölfing (2017) over different sampling time periods. While our estimate for price elasticity is in line with the findings of Fouquet (2016), this is not the case for income elasticity which was estimated at a higher value. This could be explained by the longer time period considered by Fouquet (2016) – over twelve-fold the time period used in our model – which allows for more consequential variations in income, hence potentially higher elasticities. In the case of Germany, it was found that price elasticity is not statistically significant while income and HDD elasticities are significant at the 0.1% and 1% levels. The latter are estimated to be respectively, −0.339 and 0.474 on average. Moreover, a changing trend in income elasticities was observed with a threshold value from which their signs become negative, highlighting a tendency to cut down on heating demand as disposable incomes reach higher values. This is a unique piece of information reflected in the estimates of neither Tovar-Reanos and Wölfing (2017) nor Schulte and Heindl (2017).

4. Conclusions and policy recommendations

This paper analyzed domestic heating consumption in the UK and Germany over the period 1991–2015 using non-parametric models. An easily replicated model is presented, capable of being adapted to other countries and flexible enough to include other variables that can be found relevant in other settings, therefore contributing to the methodological knowledge about how heating consumption varies in function of energy price, income and HDD variations. The development of this type of models allows providing relevant clues to design better European policies to mitigate energy poverty issues, such as, the housing energy efficiency and the adoption of more efficient and affordable domestic heating technologies. The results also reveal that each country should have its own policy frameworks to address this issue and there is no "one-size-fits-all" solution to this kind of problem, since the political, geographical, economic and social realities largely influence the type of policy to adopt.

The results show that:

1. In absolute terms, space and water heating consumption is more elastic with regard to HDD in both countries than to income and heating price, and HDD elasticity value is higher in the UK. This highlights that HDD is indeed an important variable to be included in the analysis and reveals the real influence of the weather conditions on domestic heating needs. Thus, policy measures aimed at improving building envelopes in order to minimize heat exchanges appear crucial in fighting energy wastage and its associated carbon emissions. Furthermore, policies incentivizing the adoption of solar thermal, photovoltaic or biomass technologies for domestic heating should be promoted to scale-up cleaner heat generation. This requires thorough feasibility and implementation studies.
2. Given the non-significance of price elasticity, we cannot objectively predict the impact of price policies, and energy conservation and efficiency measures to curb domestic heating consumption in Germany. Since the first Thermal Insulation Ordinance in 1977, the requirements on the thermal performance of buildings have been strengthened, and more recently with the introduction of Energy Certification of Buildings which sets more stringent compliance levels for new and existing buildings (Schlomann et al., 2015). Long-term political commitment should, therefore, be oriented towards improving the efficiency of residential buildings by enhancing thermal insulation for instance. This would help to minimize considerably the demand for space heating/cooling and enable these loads to be supplied through decentralized renewable sources, therefore resulting in CO_2 emissions reductions and cash savings for households.
3. Conversely, UK households are very responsive to energy efficiency and demand-side response measures. Thus, incentive policies to the installation of more efficient electricity, biomass or renewable-fueled heating systems such as the Domestic Renewable Heat Incentive could produce sound results. However, it is worth mentioning that the acquisition of more efficient technologies is not enough if the overall performance of buildings is not improved. Therefore, an integrated view of policies and their desired outputs is required. Furthermore, as a long-term strategy, district or local heating grids could be implemented contributing to energy poverty issues mitigation by minimizing heating prices as well as household investment needs. Most importantly, any price policy aimed at curbing domestic heating consumption such as a gas or electricity tax would have a negative impact on households living in energy poverty. Hence, should a price policy be implemented it should account for the issue of energy poverty to offset a potential rise in domestic bills. A major step undertaken by the UK to meet their energy efficiency targets is the mandatory use of condensing boilers in new buildings since 2005. However, their uptake remains marginal compared to combi-boilers (Elwell et al., 2015). Thus, it would be advisable that UK households, especially low-income ones, benefit from unwavering financial support in the acquisition of efficient heating technologies, combined with improved performance of the UK housing stock.
4. Higher income elasticity in German households trending in the opposite direction to that of the UK indicates that the wealthier German households become, the more they invest in energy efficiency solutions. In order for the German energy transition to happen and to achieve their GHG emission reduction targets, a heating transition is also required. In this context, the results seem to indicate that when a higher disposable income is available, German households would invest in infrastructural buildings improvements which in the long-run have higher potential savings. For medium and low-income households, buildings envelope modernization programs (insulation and windows) as well as the renovation and replacement of old and inefficient heating equipment have been widely encouraged by the government through the Climate-Friendly Building and Housing Strategy. This program, based on the Strategy on Energy Efficiency in Buildings and on the Alliance for Affordable Housing and Buildings, aims to support the implementation of measures to improve the performance of buildings, supporting

medium and low-income households to acquire more efficient housing at affordable prices.

Given the importance of income, price and elasticities of demand for energy services in shaping future climate policies, it is paramount that more research activities are carried out for data collection and publication. We, therefore, suggest similar studies to be performed for other European countries with higher risks of energy poverty. Moreover, it would be meaningful to enhance the present study with more disaggregated data to provide additional insights into the influence of price, income and HDD elasticities with respect to heating consumption in the UK and Germany. With the residential heating sector representing a high proportion of GHG emissions in Europe, we believe that such in-depth analyses will provide a sound scientific knowledge base in the possible policy avenues to reach climate targets while considering their impacts on energy poverty in the region.

Declaration of interest

None.

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Appendix A

Table A.1
Literature review on estimates of elasticities for energy consumption in the world, UK and Germany

Country	Time period	Consumer type	Model	Energy/Energy service	Results	Reference
G7 countries	1960–1978	All	Unspecified	Final Energy	**UK** Income elasticity: 0.43 Price elasticity: −0.18 ST | −0.41 LT **Germany** Income elasticity: 0.87 Price elasticity: −0.18 ST | −0.51 LT	(Kouris, 1983)
	Unspecified	Residential	Panel Ordinary Least Squares (Panel OLS)	Electricity, gas	**Germany** Income elasticity: 0.54 LT | −0.1404 ST Price elasticity: −4.20*** LT | 0.2694 ST (Electricity) 1.78** LT | 0.3718***ST (Gas)	(Narayan, Smyth, & Prasad, 2007)
			Panel Dynamic Ordinary Least Squares (Panel DOLS)		**UK** Income elasticity: 0.66 LT | 0.1364 ST Price elasticity: 0.60 LT | 0.0588 ST (Electricity) 1.80*** LT | −0.2179 ST (Gas)	
Portugal	1989–2010	Residential	Electricity	Pseudo-panel with quantile estimates	Price elasticity (high income): −0.891 *** (q25) | −0.526*** (q50) | −0.289 *** (q75) Price elasticity (low income): −1.432 *** (q25) | −1.108*** (q50) | −0.786*** (q75)	(Silva et al., 2017)
Spain	1999–2015	All	Diesel, gasoline	Generalized method of moments (GMM)	Price elasticity {-0.026;-0.035}LT | {-0.015;-0.019}ST (Diesel) {0.064;-0.067}LT | {-0.185;-0.193}ST (Gasoline)	(Bakhat et al., 2017)
	2001–2010	Residential	Electricity	Spatial autoregressive model with autoregressive disturbances (SARAR)	Income elasticity: 0.27** Price elasticity: −0.04**	(Blázquez Gomez, Filippini, & Heimsch, 2013)
Korea	1970–2011	Service	Electricity	VECM	Income elasticity: 1.090** LT | 0.855**ST Price elasticity: −1.002** LT | −0.421** ST	(Lim et al., 2014)
South Australia	1997–2008	All	Electricity	Semi-parametric additive model	Price elasticity: [-0.363;-0.428]	(Fan & Hyndman, 2011)
China	2008–2009	Residential	Electricity	Ordinary Least Squares	Income elasticity: [0.016;-0.063] Price elasticity: [-0.486;-0.304]	(Shi, Zheng, & Song, 2012)
Japan	1990–2007	Residential	Electricity	GMM	Price elasticity: [-0.4793;-0.3830]**	(Okajima & Okajima, 2013)
South Africa	1980–2005	All	Electricity	Kalman filter	Price elasticity: [-1.077;-0.045]	(Inglesi-Lotz, 2011)
UK	1750–2010	All	Vector-Error Correction Model (VECM)	Lighting	Income elasticity: [1.3;0.4] LT Price elasticity: [-1.2;-0.6] LT	(Fouquet & Pearson, 2012)
	1700–2010 Analyzed period: 1988–2010	All	Vector-Error Correction Model (VECM)	Domestic heating, power, transport and lighting	**Domestic heating** Income elasticity: [0.75;-0.62] LT Price elasticity: [-0.23;-0.20] LT	(Fouquet, 2016)
	1991–2007	Residential	Fixed effect	Electricity, gas	Income elasticity: 0.062*** Price elasticity: 0.983*** (Electricity) | −0.218 (Gas)	(Jamasb & Meier, 2010)

(continued on next page)

Table A.1 (*continued*)

Country	Time period	Consumer type	Model	Energy/Energy service	Results	Reference
Germany	1993–2008	Residential	Quadratic Expenditure System (QES)	Electricity, heating, transport, mobility and others	Income elasticity: 0.3988*** (Electricity) 0.4055***(Heating) Price elasticity: −0.4310***(Electricity) −0.0048***(Heating)	(Schulte & Heindl, 2017)
	2002–2012	Residential	Exact Affine Stone Index (EASI)	Heating	Income elasticity: [0;0.57] Price elasticity: [-0.6;-0.3]	(Tovar-Reanos & Wölfing, 2017)

ST: short-term; MT: medium-term; LT: long-term; * Significant at 10%; ** Significant at 5%; *** Significant at 1%; "q": quantile.

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