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The Role of Individual Preferences in Explaining the Energy Performance Gap[1]

Salomé BAKALOGLOU[2] and Dorothée CHARLIER[3]

Abstract

The aim of this research is to understand the role of socioeconomic characteristics and individual preferences in explaining the energy performance gap in the residential sector. This gap reflects the difference between the theoretical energy consumption of homes assessed by engineering models and real energy consumption. Using the ratio of the two consumption amounts to measure the gap, we perform a quantile regression to tease out the effects of preferences on the entire distribution of the energy performance gap spectrum instead of focusing on the conditional average. As a result, this research provides an original contribution: depending on the direction of the gap, our findings suggest that significant drivers include individual preferences for comfort over economy, which explain up to 12% of the gap variability, and poverty. This context should serve as a reminder to public authorities regarding the issues of rebound effect and household welfare.

Keywords: Residential energy consumption; Household preferences; Energy performance gap; Quantile regression; Quantile treatment effect.

JEL CODES: Q41; D12; C26; C21

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1. Introduction

In 2015, the residential sector represented 25.3 % of final energy consumption[4]; heating of space and water currently represents 78.6 % of that final energy consumed by households (Eurostat, 2017). EU countries have agreed on a new 2030 Framework for climate and energy including at least 27% energy savings over a status quo scenario. Energy efficiency is a powerful driver for reducing energy consumption but may not be spreading quickly enough to achieve energy targets: this could be explained by the energy efficiency gap[5]. On the other hand, the role of the dwelling's occupant in energy consumption patterns is central and must not be underestimated.

Households often combine housing attributes, energy input and climatic conditions to obtain the dwelling unit comfort that they enjoy in final consumption (Quigley and Rubinfeld, 1989). In this context, it seems pertinent to carry out an empirical analysis of the energy performance gap, which indicates the discrepancy between theoretical energy consumption predicted by engineering calculations and real energy consumption, and then identify its behavioural determinants. Understanding the origin of extreme energy performance gaps could help explain deviant consumption patterns and thus be useful for policymakers. Policy evaluations must consider not just how much a policy increases energy efficiency, but what types of consumers can be induced to become more energy efficient (Allcott and Greenstone, 2012).

The present research aims at providing an empirical contribution to the identification of how individual drivers explain the energy performance gap in the residential sector. The major focus of our research is not only to quantify the gap but also to identify low and high consumers of energy, while making a link with their individual preferences regarding energy use, energy price and revenue.

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[4] Households use energy for various purposes: space and water heating, space cooling, cooking, lighting and electrical appliances and other end uses, which mainly cover household uses of energy outside the dwellings themselves.

[5] Literature on the energy efficiency gap is abundant. For more details, see Allcott, H. and M. Greenstone. (2012). Is There an Energy Efficiency Gap? *Journal of Economic Perspectives*. 26(1):3-28, Blumstein, C. (1980). Program evaluation and incentives for administrators of energy-efficiency programs: Can evaluation solve the principal/agent problem? *Energy Policy*. 38(10):6232-6239, Gillingham, K. and K. Palmer. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy*. 8(1):18-38, Jaffe, A. B. and R. N. Stavins. (1994). The Energy Paradox and the Diffusion of Conservation Technology. *Resource and Energy Economics*. 16(2):91-122, Jaffe, A. B. and R. N. Stavins. (1994). The energy-efficiency gap What does it mean? *Energy Policy*. 22(10):804-810, Metcalf, G. E. and K. A. Hassett. (1999). Measuring the Energy Savings From Home Improvement Investments Evidence From Monthly Billing Data. *Review of Economics & Statistics*. 81(3):516.

Over the last decades, empirical research in energy economics has demonstrated that individual characteristics and occupant preferences have a crucial role in explaining final energy consumption in housing stock: by directly influencing energy consumption, these drivers could interfere with, moderate or even compromise the effects of energy-efficiency policies (Orea, Llorca and Filippini 2015). Technical data have been found to account for only 40% of final energy consumption in the residential sector (Belaïd, 2016), while socioeconomic characteristics such as revenue, household's age, tenure status, etc. account for about 33%. The specific effect of behavioural characteristics and preferences on energy consumption variability (Belaïd, 2016; Belaïd and Garcia, 2016; Cayla, *et al.*, 2011; Quigley and Rubinfeld, 1989) has frequently been highlighted, but research on the issue is rare and inconsistent (Lopes, *et al.*, 2012). Identifying and characterizing energy consumption patterns and their link to behavioural information is still a major issue.

For now, this field of empirical research is still sparse, perhaps because it requires rich datasets. The recent *PHEBUS*[6] survey, which includes complete thermal data and Energy Performance Certificates (EPCs) for more than 2000 dwellings, allows us to better understand household behaviours and their influence on energy consumption variability by controlling for home energy-efficiency heterogeneity. Given access to a formal assessment of theoretical home energy consumption with limited heterogeneity regarding the measure, we were able to measure the energy performance gap at dwelling scale. Using the "intensity of energy use[7]" indicator, i.e. the ratio between real and theoretical consumption, we were able to identify under-consumption (real consumption less than theoretical) and overconsumption (real greater than theoretical). We perform a quantile regression analysis to explain the energy performance gap spectrum, which lets us tease out the effects of preferences on the entire distribution on the energy performance gap spectrum instead of focusing on the conditional average. Finally, quantile treatment effects are implemented to how each specific variable of interest affects the gap.

As a result, this research provides an important contribution to the literature by demonstrating the prominent role of individual characteristics in explaining the energy performance gap. Depending on the scope of energy uses considered, our findings suggest that up to 12% of the

[6] http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/enquete-nomenclature/1541/0/enquete-performance-lhabitat-equipements-besoins-usages.html
[7] (Wirl 1987; Cayla, Maizi, et Marchand 2011)

gap is explained by individual preferences. Moreover, we provide evidence that poverty and financial resource availability are significant drivers that explain restriction behaviours regarding energy consumption, especially when the dwelling's energy performance is poor. On the other hand, this research demonstrates that strong preferences for comfort could explain energy overconsumption situations. These results contribute to a better understanding of the energy consumption spectrum, confirm past research assumptions and result in several public policy recommendations.

The paper is organized as follows. Section 2 presents the literature review. Section 3 describes the data. The model and the results are presented in section 4 and 5 respectively. In section 6 we discuss the results and present some policy implications. Section 7 concludes.

2. Literature review

1) Analytical framework: The energy performance gap, opposing theory and reality

The energy performance gap is defined in the literature as the difference between theoretical energy consumption assessed by engineering models after an energy audit and real energy consumption evaluated using energy bills (Allibe, 2012; Galvin, 2010; Galvin, 2014; Galvin and Sunikka-Blank, 2013). This gap has been highlighted in several studies over the past years, but little work has been done to identify the real factors influencing this gap.

In 2012, Galvin (2012) did a preliminary descriptive study with a European comparison. The authors focus on the case study of German dwellings and put forward policy implications. Their findings suggest the existence of not only an energy performance gap but also a systematic trend linking the theoretical measurement of heating energy consumption (Energy Performance Certificate measurement) and real energy consumption. The more energy efficient the dwelling is, the more the gap between the two measures grows in the direction of overconsumption. This trend is assumed to be partly linked with the rebound effect. Once dwellings have been renovated with energy-efficiency improvements, households adapt (i.e. increase) their heating comfort, leading to an increase in energy consumption. On the other hand, Galvin (2012) also introduces the concept of the "prebound effect": For less energy-efficient dwellings, real heating energy consumption is systematically lower than theoretical (on average 30% lower); this is assumed to be explained by restriction behaviours.

However, comfort preferences and behaviours are not the only reasons for a gap. Assumptions that have been made in the literature to explain the gap include the following:

- Uncertainties in the calculation method used by engineers to assess theoretical energy consumption (Allibe, 2012; Galvin and Sunikka-Blank, 2013; Galvin and Sunikka-Blank, 2014; Galvin et Sunnika-Blank 2012; Allibe 2012). This could be linked to errors in calculation, the thermal model used or incorrect assumptions (standardized occupancy, technical factors)
- Measurement uncertainties that could come from human error and subjectivity (when assessing quality or quantity of building materials or surfaces). According to experts, there is 20 to 30% uncertainty in the French EPC measure (Carassus, *et al.*, 2013).
- False assessment of the real quality of energy installations during the audit phase because of non-observability. Indeed, to stay economically affordable, EPC energy audits are probably not thorough enough to assess the real quality of dwellings' technical characteristics. This assumption comes from both technical studies (Carassus et al. 2013) and economics research (Allibe, 2012).
- Influence of socioeconomic and behavioural factors such as occupancy status, income level and number of occupants, which differs from EPC calculation assumptions or preferences (Cayla, *et al.*, 2011) .

The energy performance gap has been the focus of a few studies, but until now, none has used empirical analysis to understand what determines it. In this research, we aim to contribute to the literature on the energy performance gap by determining the role of individual attributes. More particularly, we focus on testing the hypothesis of a positive effect of individual preferences for comfort over economy, revenue and energy price to explain the gap in the French residential sector.

2) Classic determinants of energy consumption

So that our analysis uses consistent determinants that can influence the energy performance gap, we briefly review the literature to build a list of the main individual factors explaining energy demand in the residential sector. Globally, there is consensus that income, energy price, number of occupants, age of the reference person, employment status and individual preferences have a significant role in explaining energy consumption variability (Belaïd, 2016; Brounen and Kok, 2011; Brounen, *et al.,* 2013) . We thus focus on the explanatory variables of interest: energy price, revenue and preferences for comfort.

Regarding income elasticity, the effect is positive in most of the studies, which is consistent with the normal good status of energy consumption; income elasticity remains low, often less than 0.15 (Cayla, *et al.*, 2011; Labandeira, *et al.*, 2006; Nesbakken, 2001; Santamouris, *et al.*, 2007).

Energy price elasticity is always found to be positive, but estimates vary widely from -0.20 to -1.6. However, it is important to stress that price elasticity regarding energy demand may depend on the energy considered, the methodology used and the income level (Baker, *et al.*, 1989; Campbell, 2017; Fan and Hyndman, 2011; Filippini, *et al.*, 2014; Halvorsen and Larsen, 2001; Hausman, 1979; Krishnamurthy and Kriström, 2013; Krishnamurthy and Kriström, 2015; Miller and Alberini, 2016; Nesbakken, 1999; Rehdanz, 2007; Risch and Salmon, 2017; Schulte and Heindl, 2017).

Individual preferences regarding energy use refer here to the intrinsic disposition of individuals to save energy in their everyday life (Lopes, *et al.*, 2012); it does not include individual preferences that are manifested through one-time actions like the purchase of energy-efficient equipment. Indicators used as proxies for energy-saving behaviour or preferences are quite heterogeneous in the literature. For example, Santin (2011) finds that the number of hours of heating at maximal temperature explains 10.3% of the variability of heating energy consumption. The work of Hamilton, *et al.* (2013) demonstrates that energy consumption may greatly differ (by up to three times) in dwellings with similar technical characteristics. Finally, it has been found that more informative bills and advice on reasonable energy use, implying a change in individual preferences regarding energy consumption, result in 10 percent energy savings for electricity (Ouyang and Hokao 2009; Wilhite and Ling 1995). In the literature review by Lopes and colleagues (Lopes, Antunes, and Martins 2012), the synthesis shows that the savings potential from a change in energy-saving behaviours ranges from 1.1% to over 29%.

Finally, preferences for comfort are not static; they can evolve with the energy performance of the dwelling. Improving a dwelling's energy efficiency always leads to a decrease in energy consumption. However, this reduction is moderated due to the rebound effect. On average, 30% of the energy savings induced by an energy-efficiency improvement will be lost because of an increase in the comfort demand. In 2008, Sorrell and Dimitropoulos find in their literature review that the rebound effect for heating use could vary from 10 to 58% for the short-run rebound effect and from 1.4 to 60% for the long-run rebound. Erdal, *et al.* (2017) investigate the rebound effect in residential heating, using a sample of 563,000 households in the Netherlands. Using a quasi-experimental analysis through a large retrofit subsidy program, they confirm the important role of household behaviour in determining the outcomes of energy-efficiency improvement programs. They also demonstrate a significant heterogeneity in the rebound effect according to income level and actual energy use intensity. The rebound effect is strongest among lower-income groups—these households are likely to be further from their satiation level in consumption of energy services, including thermal comfort.

This literature review suggests that, indeed, energy price, revenue and individual preferences for comfort may be good candidates in explaining the energy performance gap in the residential sector.

3. Data and descriptive statistics

1) Data

To study the determinants of the gap between theoretical performance and real energy consumption, this research uses data from the PHEBUS survey, a national household energy survey conducted by the Department of Observations and Statistics (SOeS), part of the French Ministry of Ecology and Sustainable Development. The survey contains over 2000 dwelling energy audits performed by the same company and launched in 2012; theoretical energy performance measures; real energy consumption (based on energy bills); and social, economic and behavioural data on dwelling occupants. Datasets available through this survey are quite innovative as they provide us with uniform assessments of Energy Performance Certificates (EPCs) for each dwelling.

EPC measure and main calculation assumptions regarding behavioural characteristics

The theoretical energy measure available in the PHEBUS survey is the Energy Performance Certificate (EPC). EPC certification includes an energy audit realized by an approved auditor (the same for all audits) based on visual inspection and collection of technical data followed by an assessment of the theoretical energy consumption calculated by engineering models with the assumption of standardized behaviours. This measure considers three energy uses: heating, hot water production and cooling. Neither lighting consumption nor domestic appliances are considered. Characteristics such as house construction data, window and wall insulation, heating system performance and climate data are collected and merged to obtain an aggregated measure of energy consumption.

The theoretical energy consumption of each dwelling is obtained from the 3CL method[8], which allows an estimate of the predicted dwelling energy consumption, expressed as C.

$$C = Cch + Cecs + Ccool \quad (1)$$

Cch is the theoretical heating energy consumption of the dwelling, $Cecs$ the theoretical energy consumption for hot water use and $Ccool$ the theoretical energy consumption for cooling use. Cch consumption is calculated based on the heating needs of the building (Bch) multiplied by the inverse of the heating system power (Ich).

$$Cch = Bch \times Ich \quad (2)$$

where

$$Bch = SH.ENV.METEO.INT \quad (3)$$

Heating needs Bch are defined according to SH, habitable area; ENV, heating loss in the envelope and ventilation; $METEO$, which accounts for past environmental features due to dwelling location; and INT, an intermittence factor (INT), which accounts for indoor heating management (depending on heating system, building type, etc).

The main assumptions in the calculation are the following. Concerning environmental factors, the meteorological data used are the heating degree hours of the *département* (county) of reference to assess the heating needs of the building. Degree hours used are an average for the last 30 years for each *département*. Regarding heating management, 19°C is the conventional target heating temperature used in the calculation. The entire dwelling surface is considered as heated permanently during the heating period. Moreover, hot water needs are set according to the habitable area and the *département* where the dwelling is located.

In the end, this engineering calculation provides the theoretical energy consumption for each dwelling, expressed in primary and final energy, in kilowatt-hours per square meter.

Measure of theoretical and real energy performance of dwellings: the intensity of energy use ratio

As explained above, the EPC result is a quantitative assessment of final energy consumption of the dwelling in kilowatt-hours per square meter. It ranks the dwellings into energy classes (seven classes, from A to G, available in appendix A Figure 6). One of the advantages of using the EPC values provided in the PHEBUS database is that all of the dwelling energy audits are

[8] http://www.rt-batiment.fr/fileadmin/documents/RT_existant/DPE/DPE_outils/Nouvel_Algorithme_3CL-DPE_vf.pdf

carried out by the same firm, using the same calculation method, which gives us what seems to be uniform data. For this research, we use EPC measurements expressed in final energy to better match real energy consumption. Measurement of real energy consumption expressed in kilowatt-hours per square meter is based on energy bills for the year 2012. Real energy consumption measurement includes all energy consumption, regardless of the energy uses.

Thus, it is possible to calculate the intensity of energy use ratio (IEU). This indicator allows us to identify overconsumption and under-consumption situations.

The intensity of energy use indicator, first described by Wirl (1987) and then Cayla, *et al.* (2011), is defined as follows:

$$IEU = \frac{Final\ energy\ consumption\ (based\ on\ energy\ bills)}{Theoretical\ energy\ consumption\ (EPC)}$$

When the ratio becomes well above one, it means that the dwelling is "overconsuming" in comparison with its theoretical measure of energy consumption; if it is smaller, the dwelling is said to be to "under-consuming". The energy performance gap combines the instances when IEU significantly differs from one. This research aims to explain these high and low measures of the ratio using socioeconomic and environmental data.

However, we would like to make it clear that, in the analysis that follows, the scope of the energy uses included in the numerator and the denominator is not systematically the same. In addition to basic energy uses, real energy consumption includes specific electricity and cooking energy uses that are not considered by the theoretical measure of energy consumption assessed in the survey. EPC only includes main energy uses: hot water and heating energy. Thus, when we consider the intensity of energy use indicator, only extreme values can be considered as interpretable in terms of the energy performance gap. Heating and hot water energy uses account for approximately 61% and 12%, respectively, of dwelling global energy consumption. To complete our analysis, we also consider the IEU for a subsample of dwellings that are heated with gas and use gas for hot water. For this sample, we excluded all other energy uses in order to get a comparable basis between the EPC measure and real energy consumption in our IEU indicator. As this subsample includes only 517 observations, we use it to test the robustness of the analysis realized on the global sample.

Individual preferences for comfort

In the PHEBUS dataset, information is also available on households' stated preferences. For each end use (heating, hot water and electricity), it is possible to know whether households favour comfort or energy savings. It is therefore possible to have a scale of preferences. A strong preference for comfort will be measured as a declared preference for each end use, a medium preference as a declared comfort preference for two out of three end uses and finally a low preference as a single declared preference for comfort. In this dataset, other variables can also be used as a proxy for comfort: for example, the heating temperature.

We check the consistency between stated preferences and behaviour (see Table 6 in the appendix). While we are aware that behaviour is also reported, it is a way to control the consistency of the answers. In general, households that say they prefer comfort exhibit less economical behaviour. Moreover, households are distributed fairly evenly between the different levels of preference (between 21% and 28%) whatever the sample (whole or gas sample, Table 7).

More than 56% of households who have a stated preference for one end use have the same stated preference for the other two end uses (Table 8).

Energy price

The survey provides information on the type of energy cost (for gas and electricity) and the power required per type of fuel used (electricity, gas, oil). The power required and the type of energy cost depend on the type of fuel used for the heating system and hence on the energy mix as well as the number of rooms (or the surface area). At the end, we face different energy costs per energy mix composition and end use.

However, no information is provided on the energy price itself. We thus supplemented the PHEBUS database with information on the energy rate and the subscription cost for each type of energy (oil, gas, electricity and wood): the energy cost depends on the power required and the type of cost in 2011 and 2012. This information is available in the PEGASE database provided by the French Ministry of Energy.

Finally, for each household, it is possible to calculate a weighted energy cost depending on the energy mix and the structure of energy consumption. With a weighted energy cost, we have a specific rate of energy for each household. The formula is the following:

$$energy\ price_i = \sum_{j=1}^{n} \frac{volume\ in\ kwh_{ijt} \times energy\ price_{jt}}{total\ volume\ in\ kwh_{ij}}$$

where j represents the type of fuel, i the household and t the type of cost for a specific energy (electricity or gas).

Climate data for 2012

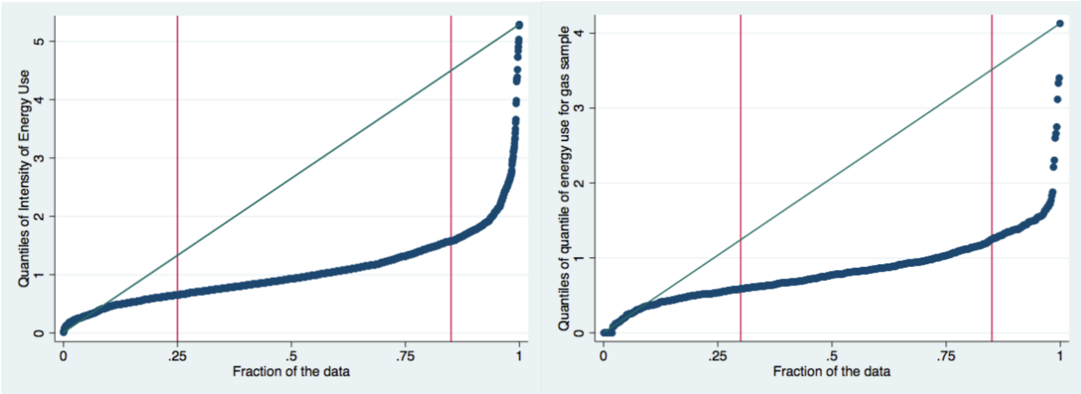
Our dataset also provided information on the department where each dwelling is located. This information was matched with 2012 meteorological data from Meteo France (annual heating degree days by *département*) in order to have a proxy for the real meteorological conditions of 2012. As theoretical energy consumption (EPC) integrates climate data from the past 30 years, using real heating degree days for 2012 is assumed to influence the gap between theoretical energy consumption and effective energy consumption.

2) Descriptive statistics

The main descriptive statistics of the variables used in the model are summarized in Table 1 and in appendix B (Table 9). The final sample contains 1,853 observations after removing missing values. In the rest of this research, we also use a restricted sample composed of 517 dwellings with gas heat and gas-heated water.

In Figure 1, quantile plots are drawn for all observations and for the gas sample. According to Figure 1, the quantile plot for the whole sample has three different regions. The first includes a horizontal line for zero IEU - we call such entities digit preferences. The second region, with relatively high density, extends from just above zero up to about an IEU value of 2. Above it is a region with low and declining density. All the symbols are below the main diagonal: the distribution is skewed to the right. The maximum IEU is 5.29 and the average value is 1.05, while the median is equal to 0.93. Single outliers are also easily identified, for example the households with an IEU higher than 3. There are 120 households consuming more than twice their theoretical energy. For the gas sample, the median is equal to 0.77 and the average value is 0.83.

Figure 1: Distribution of the IEU



Data: PHEBUS 2012, authors' calculations

The descriptive statistics of household characteristics and dwelling attributes (see Table 1 of descriptive statistics by IEU quantiles) lead us to set the following assumption: Being in an "abnormal situation", meaning having either a very high IEU value (energy overconsumption) or a very low IEU value (energy under-consumption) could be linked to household socio-demographic characteristics, household preferences, economic and environmental context or home characteristics.

Table 1: Descriptive statistics (global sample and gas sample)

	Global sample						Gas sample			
	All observations		**20%***		**85%**		**30%****		**85%**	
	Mean	**Std, Dev**	**Mean**	**Std, Dev**	**Mean**	**Std, Dev**	**Mean**	**Std, Dev**	**Mean**	**Std, Dev**
Intensity of Energy Use	1.055	0.632	0.564	0.023	1.516	0.037	0.567	0.0151	1.323	0.0389
Average final energy consumption (kWh/m2/year) (based on bills)	168.282	95.496	129.428	56.310	191.692	85.567	166.170	45.111	215.828	70.615
Average EPC expressed in final energy (m2/CU)	265.007	134.075	309.968	137556	209.673	99.797	235.394	76.045	153.203	57.899
Average annual disposable income per household	40029	23920	38047	26233	43336	20461	38113	21387	45242	25031
Energy price in 2012	0.0942	0.0271	0.1012	0.0273	0.0923	0.0261	0.0831	0.0194	0.0795	0.0174
% of no comfort preference	0.272	0.445	0.295	0.458	0.191	0.395	0.385	0.496	0.000	0.000
% of low preference for comfort	0.212	0.409	0.189	0.394	0.157	0.366	0.077	0.272	0.308	0.471
% of medium preference for comfort	0.222	0.416	0.253	0.437	0.382	0.489	0.231	0.430	0.308	0.471
% of strong preference for comfort	0.294	0.456	0.263	0.443	0.270	0.446	0.308	0.471	0.385	0.496
% of comfort preference for heating	0.568	0.496	0.547	0.500	0.618	0.489	0.423	0.504	0.769	0.430
% of comfort preference for hot water	0.557	0.497	0.537	0.501	0.640	0.483	0.615	0.496	0.769	0.430
% of comfort preference for electricity	0.413	0.492	0.400	0.492	0.472	0.502	0.423	0.504	0.538	0.508
Mean heat temperature (°C)	19.93	1.49	19.83	1.56	20.22	1.43	19.75	1.63	20.10	1.23
Unit of consumption	1.69	0.54	1.55	0.51	1.89	0.53	1.65	0.66	1.95	0.59
Average age of the dwelling’s reference person	56.19	15.13	58.51	15.36	51.34	14.79	54.08	16.04	52.92	16.57
Average number of appliances	16.24	14.06	13.94	5.14	16.45	5.47	13.00	6.39	15.88	5.81
Number of showers per week	1.06	3.69	0.76	1.62	1.11	2.39	1.50	2.30	1.96	3.54
Number of baths per week	13.11	9.69	11.25	12.71	17.20	10.04	12.58	11.25	15.42	9.97
Cold problem	0.161	0.367	0.179	0.385	0.101	0.303	0.231	0.430	0.077	0.272
Limit heating consumption	0.235	0.424	0.326	0.471	0.157	0.366	0.346	0.485	0.192	0.402
Fuel poor by the 10% definition	0.098	0.298	0.105	0.309	0.101	0.303	0.038	0.196	0.077	0.272
Monetary poor (60% median)	0.195	0.396	0.242	0.431	0.135	0.343	0.308	0.471	0.231	0.430
Renovation work	0.514	0.500	0.495	0.503	0.438	0.499	0.462	0.508	0.500	0.510
Never switch off the heating system	0.384	0.487	0.242	0.431	0.483	0.503	0.346	0.485	0.538	0.508
Adjust the heating system	0.870	0.336	0.884	0.322	0.876	0.331	0.923	0.272	0.923	0.272
Windows closed during heating	0.008	0.090	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Heating Degree Days	2496.06	383.007	2474.35	382.868	2492.73	401.848	2601.76	247.323	2398.93	394.970

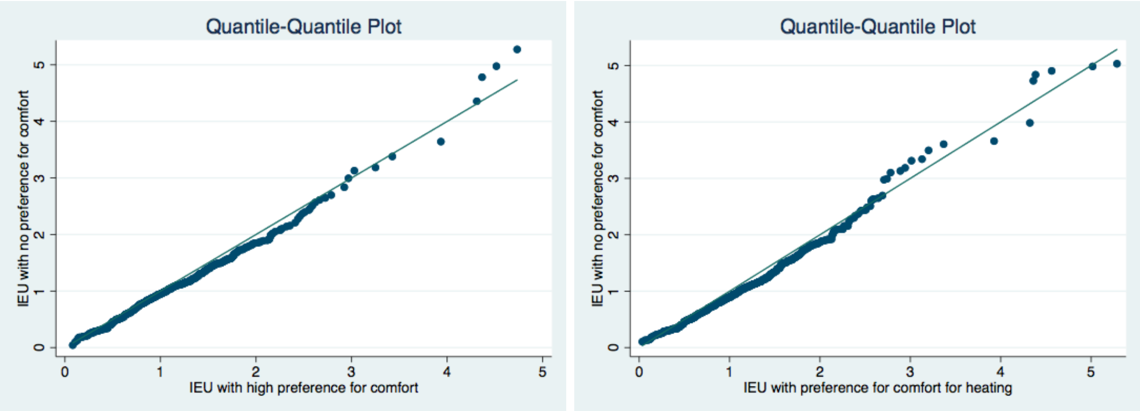
*Quantiles of IEU Source: authors’ calculations, PHEBUS 2012 **the choice of 30% for gas is to ensure comparison of IEU values between samples.

Role of preferences for comfort over economy

According to Table 1, households with no preference for comfort represent 29.5 % of quantile 0.2 as opposed to only 19.1% for quantile 0.85. This difference is reinforced in the gas sample, with 38.5% in quantile 0.3 versus 0% in quantile 0.85 (see Table 10 in the appendix for the IEU value for the gas sample). Still in the gas sample, the share of households declaring a strong preference for comfort in heating represents 76.9% of the population that overconsumed but only 42.3% of households that under-consume. People who declare having preferences for comfort are overrepresented in households that overconsume.

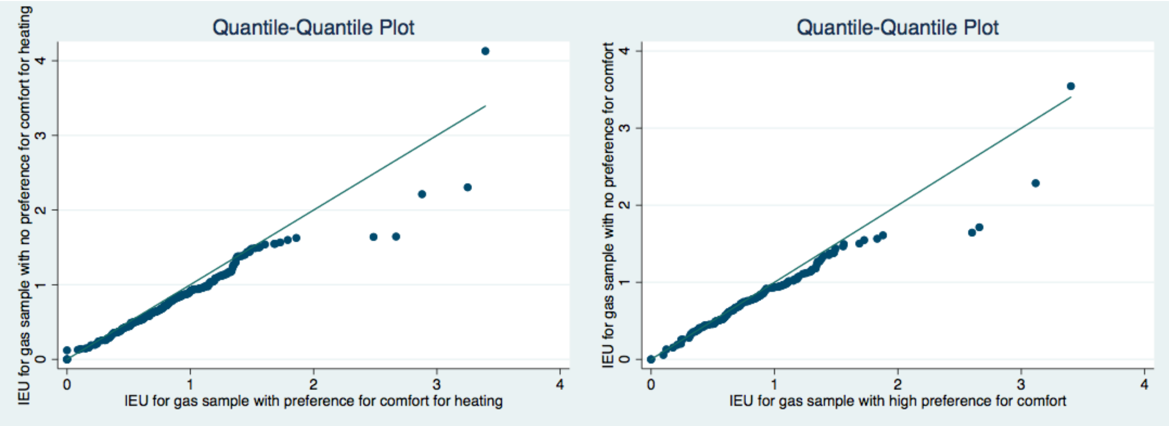
According to Figures 2a and 2b, we can also see that most data points are to the right of the main diagonal on both graphs. This means that the distribution values on the x-axis are usually higher than those on the y-axis. In our case, this means that households with strong preferences for comfort and preferences for comfort in heating have a higher IEU than households with no preference, in both samples. This confirms the descriptive statistics in Table 1 that show that preferences for comfort over economy are declared more often for high values of IEU (0.85 quantile) than for low values (0.20 quantile). Heating use makes up on average 61% of global energy consumption; its influence could thus be meaningful in impacting global energy consumption, which is confirmed with the gas sample.

Figure 2a: Quantile plot according to preferences for comfort (global sample)



Data: PHEBUS 2012, author calculations

Figure 2b: Quantile plot according to preferences for comfort (gas sample)



Data: PHEBUS 2012, authors' calculations

Energy price and revenue

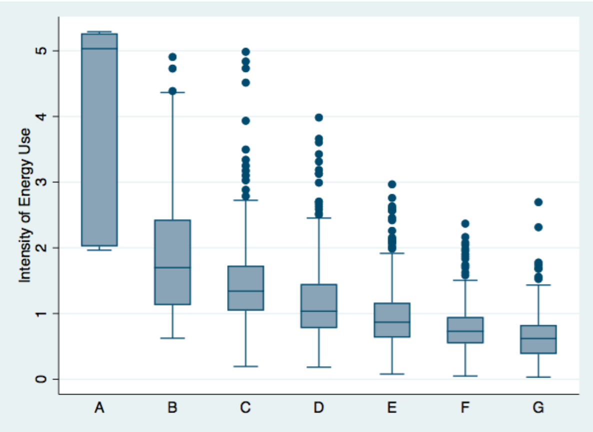
Higher energy price and lower revenue are found in the first quantiles of IEU. Energy price is 8.8% higher on average in the 0.20 quantile than in the 0.85 quantile. Revenue is 13.9% lower on average in the 0.20 quantile than in the 0.85 quantile.

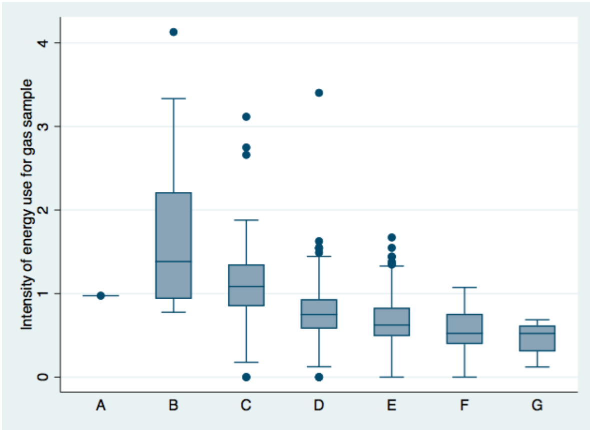
Moreover, the percentage of households in monetary poverty also implies the potential role of financial resources in explaining under-consumption: the percentage of these households is much larger (two times higher) in the 2.0 IEU quantile than in the other quantile. These results lead to the hypothesis of significant effects of energy price (negative effect) and income elasticities (positive effect) on IEU, resulting in restriction behaviour relative to energy use.

Energy efficiency of the dwelling and IEU

Our analysis of PHEBUS data shows that intensity of energy use follows a visible trend linked to the energy-efficiency level of homes; similar results are found in Sunnikka-Blank and Galvin's research (2012). In order to investigate the characteristics of high IEU value, we compare values according to energy labels. For the less energy-efficient dwellings, energy is under-consumed, meaning that either the theoretical energy measure is over-assessed or households strictly restrict their energy consumption (Figure 3). The inverse trend is observable for very energy efficient-dwellings: energy is overconsumed in energy classes A and B due to what is usually called the rebound effect.

Figure 3: Intensity of energy use by energy class for the global and gas samples





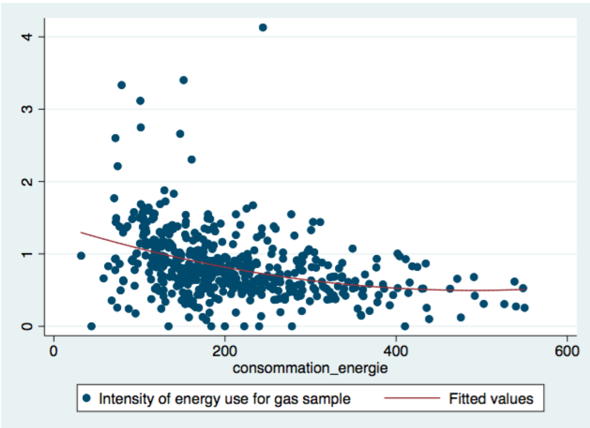
Global sample

Gas sample

Data: PHEBUS 2012, authors' calculations

If we consider the dwellings with gas heat and gas-heated water, the relationship between theoretical energy consumption and IEU can be graphically modelled (Figure 4). We note that the link is statistically significant. There is a clear trend in the data: the more energy efficient the dwelling is, the higher the IEU. Under-consumption is noticeable for dwellings with a theoretical energy consumption over 200 kwh/m2 (Classes E-F-G).

Figure 4: Relationship between IEU and EPC measure (expressed in final energy kwh/m^2) in the gas sample, 517 observations.



In line with the literature, we thus assume that the trend observed in the global and gas samples could come in part from a "comfort effect" or from restriction behaviours regarding energy consumption (Sunikka-Blank and Galvin, 2012). This belief is strengthened by descriptive statistics in Table 2 that show that income and preferences for comfort seem to be linked with the energy efficiency of dwellings. Moreover, preferences are also linked to income (see Table 11 in the appendix).

Table 2: Individual preferences for comfort, behaviour and poverty by class

	Class A	Class B	Class C	Class D	Class E	Class F	Class G
Number of observations	5	39	260	526	554	261	208
Percentage of households preferring comfort over economy for:							
Heating	80%	64%	57%	58%	58%	51%	57%
Hot water	60%	67%	58%	58%	57%	52%	47%
Specific electricity	40%	38%	43%	44%	41%	41%	39%
Strong preference for comfort*	20%	31%	29%	31%	31%	27%	25%
Medium preference for comfort*	60%	28%	25%	24%	22%	18%	21%
Low preference for comfort*	0%	21%	21%	20%	21%	23%	24%
Limit heating consumption	0%	13%	22%	20%	23%	31%	27%
Monetary poor	0%	15%	12%	13%	18%	31%	37%
Report cold problem	0%	7.7%	10%	13.3%	15.3%	21.8%	27.4%
Fuel poor	20%	7.7%	3.8%	5.5%	10.3%	15.7%	19.7%
Income (st dv)	51067 (22293)	49733 (40628)	44872 (24804)	43337 (24990)	38685 (20553)	36462 (284804)	31578 (19507)

**This variable is compounded from PHEBUS data: strong preference for comfort means that the household declared that it prefers comfort over economy for all three energy uses: specific electricity, heating and hot water; medium preference means that this preference for comfort concerns two of the three energy uses; and finally, low preference means that the preference for comfort concerns only one energy use.*

Source: PHEBUS Survey 2012

4. Model

1) Quantile regressions

We perform a quantile regression analysis to understand the drivers of the energy performance gap; this method lets us tease out the effects of preferences on the entire distribution of the energy performance gap spectrum instead of focusing on the conditional average.

By using quantile regressions, we can specify the differentiated impacts of socioeconomic determinants on several energy consumption levels (under-consumption, normal consumption and overconsumption patterns), which are estimated by the *Intensity of Energy Use* (IEU) indicator. The quantile regression method is an extension of ordinary regression[9]. It was first introduced by Koenker and Bassett (1978) and generalizes the concept of the univariate quantile to a conditional quantile given one or more covariates. Thus, it is less restrictive than the OLS method because slope coefficients can vary across the chosen quantiles of the dependent variable and hence are not only mean estimations. This method makes it possible to detect whether explanatory determinants have the same effects for extreme values of the dependent variable (for example, for 5th, 25th and 75th quantiles) and to quantify these effects. In addition to giving robust coefficient estimations with respect to outliers, in our case, it is also useful to assess the variability of the main determinants of over- and under-consumption, behaviours represented by extreme values of our dependent variable *Intensity of energy use.* By doing so, we may detect differential impacts of revenue, energy price or individual data such as preferences on the level of consumption. As an example, the research of Kaza (2010) uses this method to estimate the impacts of numerous determinants on different quantiles of energy consumption in the US residential sector. It shows that the effects of neighbourhood density, housing size and housing type on the tails of the distribution are substantially different.

We have the θ^{th} quantile, generally defined as:

$$q_{\theta}(Y) = inf\{y: F_Y(y) \geq \theta\}, 0 < \theta < 1$$

The linear quantile regression in our model can be formalized as follows:

$$y_i = x_i'\beta_\theta + u_i \text{ with } Q_\theta(y_i \;/\; x_i) = x_i'\,\beta_\theta$$

In our model, y is the vector of *Intensity of energy use* data (in logarithmic form), x is a vector of all the regressors, β is the vector parameters to be estimated and u is a vector of residuals. $Q_\theta(y_i \;/\; x_i)$ is the Q^{th} quantile of y_i given x_i. The θ^{th} QR estimator minimizes the objective function over $\widehat{\beta_\theta}$ (Cameron and Trivadi, 2010):

$$\mathrm{Q}(\beta_\theta) = \sum_{i:yi \geq x_i'\beta}^{N} \theta|y_i - x_i'\beta_\theta| + \sum_{i:yi < x_i'\beta}^{N} (1-\theta)|y_i - x_i'\beta_\theta|$$

[9] Before choosing quantile regression, we ensure the absence of energy price endogeneity with the dependent variable. We introduce as an instrument the lag of energy prices in order to deal with the simultaneity problem. This instrument has already been used in previous studies to deal with the same problem (Risch and Salmon, 2017; Robert, 2015). We confirm the validity of our instruments and the absence of endogeneity.

If $\theta = 0.75$, much more weight is placed on predictions for observations with $y \geq x'\beta$ than for observations with $y < x'\beta$. Finally, asymptotic and bootstrapping methods are used to obtain the standard errors and confidence limits for coefficient estimates.

For our global model, we first use quantiles 0.2 and 0.85 to determine the specific effects of the determinants on extreme performance gaps. Quantile 0.2 represents an IEU equal to 0.56 and quantile 0.85 represents an IEU equal to 1.52. Quantile (0.2 0.85) also specifies that two equations are to be estimated, one for each quantile. For the gas sample, we use quantiles 0.3 and 0.85 (an IEU value of 0.57 and 1.32, respectively) in order to ensure a consistent comparison between the global sample and the gas sample.

Thus, quantile regression will allow us to determine the effects of individual preferences and energy prices on the intensity of energy use. The coefficient that will be obtained for each identified quantile of IEU tells us how the tails of intensity of energy use react differently to an increase in each variable of interest. While the price of energy should have a negative effect on the energy performance gap, we expect a positive impact for income and individual preferences for comfort.

The other explanatory variables used are the following: the number of heating degree days, the number of consumption units, the ability to adjust the heating system, the age of the reference person, the practice of not opening windows during the heating period and the practice of switching off the heating system when windows are open. We run several quantile regressions to test the effect of three related variables on IEU: strong preferences for comfort over economy (regression 2) and preferences for comfort over economy for heating use (regression 3) and heating temperature (regression 4). We also present our results compared to an OLS estimation (regression 1). Finally, robustness tests of parameters (especially when we introduce income and preferences separately) are presented in appendix C (Table 12).

2) Quantile treatment effects

When the objective is to assess the causal effect of a specific explanatory variable on the entire distribution of a variable of interest, the estimation of quantile treatment effects (QTEs) may be useful (D'Haultfoeuille and Givord, 2014). QTEs make it possible to evaluate the effect of a binary dummy variable T, which corresponds to the difference between the quantiles of the distribution in the population for the two states of the dummy. Here, we assume that each observation has two potential IEUs: Y_1 corresponds to the IEU the household can expect with the dummy in state 0 (for example, absence of strong preferences for comfort over economy) and Y_1, the IEU the household can expect with the dummy in state 1 (for example, having strong preferences for comfort over economy). Two distributions, F_{Y0} and F_{Y1}, are associated with these two potential IEUs. The τ^{th} "quantile treatment effect" is defined as the horizontal distance between the two distributions (Doksum, 1974).

$$\delta_q = q_{\tau}(Y_1) - q_{\tau}(Y_0)$$

This program uses a weighting strategy. The estimator proposed by Firpo (2007) is used in our case because unconditional QTEs under exogeneity are estimated.

In our research, we test the effect on the two extreme quantiles of IEU (0.2 and 0.85) of the following variables: preferences for comfort over economy (strong preferences and preferences for comfort in heating use, hot water use and specific electricity use), poverty, cold issue, restriction on heating consumption and fuel poverty. Quantile treatment effects are also run on the gas sample. Our results are presented in the following section.

5. Results

The general trend of our coefficient estimates (Regressions 2, 3 and 4) is consistent with our use of the quantile regression in understanding the drivers of the energy performance gap: several of our explanatory variables do have a differentiated effect varying across IEU quantiles (see Table 3).

Table 3: Results of quantile regressions on global sample

	OLS	Quantile regression							
		Regression 1		Regression 2		Regression 3		Regression 4	
		Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85
Energy price (log)	-0.104***	-0.0976***	-0.121***	-0.105***	-0.147***	-0.107***	-0.107***	-0.0956***	-0.140***
	(0.0209)	(0.0268)	(0.0375)	(0.0225)	(0.0367)	(0.0256)	(0.0365)	(0.0244)	(0.0335)
Income (log)	0.0744**	0.111**	0.106*	0.0878*	0.141**	0.0677	0.124**	0.0662	0.130***
	(0.0334)	(0.0485)	(0.0563)	(0.0475)	(0.0550)	(0.0526)	(0.0559)	(0.0456)	(0.0502)
uc	0.403*	0.485*	0.725*	0.436	1.016***	0.280	0.845**	0.291	0.967***
	(0.223)	(0.290)	(0.370)	(0.286)	(0.360)	(0.315)	(0.357)	(0.277)	(0.345)
age	-0.00179***	-0.00179***	-0.00212**	-0.00211***	-0.00209**	-0.00212***	-0.00186**	-0.00175***	-0.00172*
	(0.000434)	(0.000660)	(0.000860)	(0.000588)	(0.000832)	(0.000588)	(0.000862)	(0.000576)	(0.000934)
Heating degree days (log)	-0.200***	-0.107**	-0.324***	-0.104***	-0.298***	-0.113***	-0.306***	-0.118***	-0.324***
	(0.0366)	(0.0433)	(0.0693)	(0.0391)	(0.0674)	(0.0423)	(0.0648)	(0.0435)	(0.0694)
Never switch off the heating system	0.0459***	0.0487***	0.0589***	0.0368**	0.0420*	0.0383***	0.0402*	0.0506***	0.0602**
	(0.0131)	(0.0163)	(0.0227)	(0.0148)	(0.0234)	(0.0143)	(0.0225)	(0.0157)	(0.0238)
Possibility to adjust the heating system	0.0335*	0.0528*	0.00150	0.0535**	0.00846	0.0681**	0.00562	0.0565*	-7.07e-05
	(0.0196)	(0.0279)	(0.0326)	(0.0249)	(0.0352)	(0.0270)	(0.0345)	(0.0306)	(0.0308)
Windows closed during the heating period	-0.000703	-0.0675	0.0179	-0.115	0.0555	-0.0767	0.0107	-0.0606	0.0434
	(0.0816)	(0.118)	(0.156)	(0.120)	(0.150)	(0.114)	(0.150)	(0.109)	(0.186)
Strong preference for comfort				0.0450***	0.0695***				
				(0.0142)	(0.0253)				
Preference for comfort in heating						0.0418***	0.0483**		
						(0.0144)	(0.0217)		
Heating temperature								0.0186***	0.0249***
								(0.00433)	(0.00619)
Interaction parameter	-0.0326	-0.0428	-0.0626*	-0.0373	-0.0895***	-0.0227	-0.0732**	-0.0240	-0.0852***
	(0.0210)	(0.0273)	(0.0352)	(0.0271)	(0.0340)	(0.0297)	(0.0339)	(0.0260)	(0.0323)
Constant	1.170**	-0.102	2.048***	0.0802	1.393**	0.341	1.705**	0.0793	1.223*
	(0.456)	(0.642)	(0.723)	(0.614)	(0.702)	(0.673)	(0.683)	(0.630)	(0.664)

Note: standard errors in parentheses *** p<0.01, ** p<0.05, ***p<0, 3000 replications

Table 4: Estimates for quantile treatment effects for global sample and gas sample

Global Sample (1,853 observations)	Q=0.2		Q=0.85	
	Coefficient	Bootstrap Std. Err.	Coefficient	Bootstrap Std. Err.
Strong preference for comfort	0.0320**	0.0141	0.0498**	0.0211
Comfort preference for heating	0.0421**	0.0169	0.0466**	0.0217
Comfort preference for hot water	0.0284*	0.0148	0.0185	0.0204
Comfort preference for electricity	0.0146*	2.0100	0.0521**	0.0202
Cold problem	-0.0512***	0.0242	-0.0580	0.0426
Limit heating consumption	-0.0397*	0.0144	-0.0298	0.0283
Fuel poor by the 10% definition	0.0249**	0.0195	-0.0073	0.0376
Monetary poor (60% median)	-0.0868*	0.0176	-0.0867	0.0256

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1, 3000 replications

Gas Sample (517 observations)	Q=0.3*		Q=0.85	
	Coefficient	Bootstrap Std. Err.	Coefficient	Bootstrap Std. Err.
Strong preference for comfort	0.0447653	0.0556478	0.1224759**	0.062161
Comfort preference for heating	0.1155424**	0.0537769	0.1233805*	0.0655496
Comfort preference for hot water	0.0648034	0.0617895	0.1277027**	0.0655822
Cold problem	-.006735	0.0785468	-0.1847566**	0.0851247
Limit heating consumption	-0.108445	0.0665022	-0.1276259	0.0809505
Fuel poor by the 10% definition	0.1248077	0.1408438	0.1395232	0.1123413
Monetary poor (60% median)	-0.1223761*	0.0664371	0.0125486	0.0912034

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1, 3000 replications
*the 0.3 quantile corresponds to a IEU of about 0.5 in the gas sample

Prices and income elasticities

Energy price elasticity is significant and negative for all the quantiles of IEU, which is consistent with previous findings in the energy economics literature. Extreme energy performance gaps (low and high IEU quantiles) are often explained by energy price elasticity (household reaction to a change in energy price). However, regressions show that energy price elasticity is slightly lower for the first quantiles of IEU (0.2) than for the 0.85 quantile, around -0.11 and -0.15 respectively. Thus, energy price variability affects under-consumption less broadly than it does overconsumption situations.

Given this result, under-consumption seems to be associated with energy restriction behaviours. Indeed, the fact that households restrict their consumption of energy to the level needed to achieve only their basic needs (low IEU) is consistent with a lower sensitivity to changes in energy price. On the other hand, dwellings with overconsumption are likely to have more flexibility in their energy consumption, which can explain the greater energy price elasticity.

Income elasticities are in line with previous findings in the economics literature, i.e. between 0.06 and 0.14: energy is a normal good (Cayla, *et al.*, 2011; Labandeira, *et al.*, 2006; Nesbakken, 2001; Santamouris, *et al.*, 2007). However, coefficients vary according to IEU quantiles: households with a high IEU have a higher income elasticity, which could underscore an ability to increase their equipment rate (and their electricity consumption).

Monetary and fuel poverty

The poverty situation of the household explains up to 8.7% of the energy performance gap. Quantile treatment effects provide evidence that being poor (living below the poverty line) has a significant, negative effect on the lower quantile of IEU considered. This result is more pronounced in the gas sample: households restrict their heating consumption in monetary poverty (12.2% of the gap is explained by poverty in the gas sample case). In our descriptive statistics, we demonstrated that poor households are generally found in the lower value of IEU; thus, under-consumption is assumed to be strongly related to the limited economic resources of the household.

Otherwise, a link can be established with the findings of Meier, *et al.* (2013) who found that low-income households had lower energy price elasticities than high-income households. As we demonstrated in our descriptive statistics (Table 1), low-income households are more numerous in the lower quantile of IEU.

Finally, the role of poverty in explaining low IEU is even stronger if we remember the link between dwellings with poor energy efficiency (meaning high energy expenditures) and under-consumption situations (low IEU): as poor households face high energy expenditures because of the weak energy performance of their homes, we can assume that they are more likely to restrict their energy consumption. This is also in line with the effect of the variable called "limit heating consumption" (Tables 4 and 5), whose effect is significant and has a negative effect only on the first quantile of IEU considered, in both the global and gas samples.

Individual preferences and behaviour

The effects of individual preferences and behaviours are significant. Regressions show that the binary variable "strong preferences for comfort over economy" has a positive effect, growing with the quantiles of IEU. Preferring comfort over economy for all three energy uses (heating, hot water and specific electricity) leads to an increase by almost 5% of the IEU for the 0.85 quantile, meaning that individual preferences contribute 7% of the variability in the gap in overconsumption situations (versus 4.5% for 0.2 IEU quantiles). If we look at the effect of preferences for comfort in heating use for each quantile of IEU (regression 3), the values of the coefficients found are quite similar to those estimated in regression 2, which indicates that preferences for comfort in heating use are a prevalent driver in explaining the energy performance gap. This is consistent with the fact that 61% of the global energy consumption comes from residential heating needs. Preferences for comfort in specific electricity also contribute to explaining the gap for high IEU (Tables 4-5, quantile treatment effect); we note that their effect on high IEU is greater than the one found for preferences for comfort in heating. Even though it only accounts for about 20% of energy consumption, a significant portion of high-energy consumption patterns can be explained by specific electricity consumption.

Our estimates show that individual preferences for comfort do have an impact in explaining the energy performance gap, but this impact seems limited (3 to 7%). However, this result has to be viewed cautiously, as the scopes of theoretical and real energy consumption considered in the IEU indicator are not equivalent: real energy consumption includes all types of energy consumption regardless of the energy uses, whereas theoretical energy consumption only includes consumption from heating and hot water energy uses. As a robustness check, the results of the quantile treatment effect on the gas sample confirm that preferences for comfort in heating have a significant role in explaining the energy performance gap. Thus, up to 12% of the energy performance gap can be explained by individual preferences for heating.

Finally, never switching off the heating system has a significant positive effect on IEU; this effect is quite homogeneous over the different quantiles of IEU, unlike the possibility of adjusting the heating system, which has a positive effect only on the lower quantile of IEU.

Household characteristics and climate

Besides the roles of energy price and preferences in explaining the energy performance gap, our research highlights the role of several other salient drivers (see Tables 4-5). The number of consumption units has a significant positive effect on IEU; this effect is higher for the 0.85

quantile representative of overconsumption. The age of the reference person has a quite homogeneous negative effect over the different quantiles of IEU.

Finally, we note that the factor with the most impact on explaining the energy performance gap is heating degree days. The effect is significant and negative for all quantiles of IEU. However, the effect is much greater for the high quantiles of IEU. The significant impact of this climate variable could be the result of either a false assessment of the climate factors in developing the theoretical measure of energy consumption or an important behavioural adaptation of households to local climate change that is not considered in models: an increase in heating degree days (cold weather) leads to a decrease in IEU. Households with high IEU values can better adjust their consumption in severe winter (perhaps to avoid extra costs). Heating needs might thus be under-assessed for freezing temperatures.

6. Discussion and policy implications

To sum up the main results, we observe that the effect of heating or strong preferences for comfort is almost twice as large in the last quantile of IEU as it is in the first quantile of IEU; this confirms the more important role of preference for comfort in explaining the gap in overconsumption situations. This result is confirmed in regression 4 (Table 3), where we also note a growing trend in the effect of heating temperature on IEU quantiles: the indoor temperature, a proxy of comfort preferences, has more impact on high quantiles of IEU than it does on lower ones. On the other hand, energy under-consumption, i.e. low IEUs (Q=0.2), are partly explained by monetary and fuel poverty (Table 3 and 4).
In the current political context that is primarily focused on energy efficiency issues in the residential sector, the goal of this discussion is to use our main results to provide key elements of analysis to policymakers with this energy efficiency perspective. In that sense, we would point to Figure 3, which identifies a strong relationship between IEU and the energy class of each dwelling. The graph demonstrates that overconsumption situations are more likely to be found in energy-efficient dwellings, whereas under-consumption situations are more frequent in dwellings with a very poor energy performance.

A new perspective in understanding the rebound effect in the residential sector

Our results can be linked to the issue of the rebound effect and provide key insights. The direct rebound effect reflects the potential increase in the demand for a service (here energy use) after an improvement in its efficiency (Freire-González, 2017; Greening et al., 2000). This effect is visible in our cross-sectional dataset (figure 5). Indeed, the real energy consumption does not decrease at the same rate as the theoretical energy consumption; it decreases more slowly. If we look at figure 5, our findings suggest that a 100% improvement in home energy efficiency leads to a 58% reduction in real energy consumption, meaning that 43% of energy savings are "lost" (rebound effect): this could be partially justified by comfort improvement when energy service costs decrease.

If we consider the households in our database who report having increased heating after energy-efficiency work, a t-test demonstrates that they statistically overconsume (IEU equal to 1.24 for people declaring a direct rebound effect versus 1.0 for the others). They represent 6.3% of the households in the sample who have undertaken energy-efficiency renovations. This result underlies the fact that energy efficiency must be accompanied by moderation in energy consumption if energy goals are to be achieved.

However, with regard to our results, the cross-sectional results suggest that the "rebound effect" does not have the same meaning for everybody. If we consider the households who live in a sub-standard situation in the first place, meaning a dwelling with very poor energy performance and an associated low IEU (the household severely restricts its energy consumption), an increase in energy efficiency will lead to a relaxation of the financial constraints related to energy consumption, which leads to a relative increase in its energy consumption (the rebound effect process). However, in this case, these households will increase their energy consumption in order to achieve or approach the "standard" or "legitimate" comfort level because they were previously limiting their energy consumption well below the norm (Nösperger, *et al.*, 2017). In this specific case, the rebound effect means households simply catching up with standard comfort standards; thus, here, the recommendation of energy consumption moderation is much less relevant.

Figure 5a: Real energy consumption vs theoretical energy consumption: y, real energy consumption and x, the theoretical energy consumption. Gas sample. Data: PHEBUS, 2012. The red curve stands for the bisector (theoretical energy consumption). If the gap between the two curves comes only from behavioural data, the "rebound effect" should be equal to $(1 - 0.58) \times 100 = 42\%$. *However, here,* *it is probably less than 43% because other drivers also explain the energy performance gap. Data are cross-sectional.*

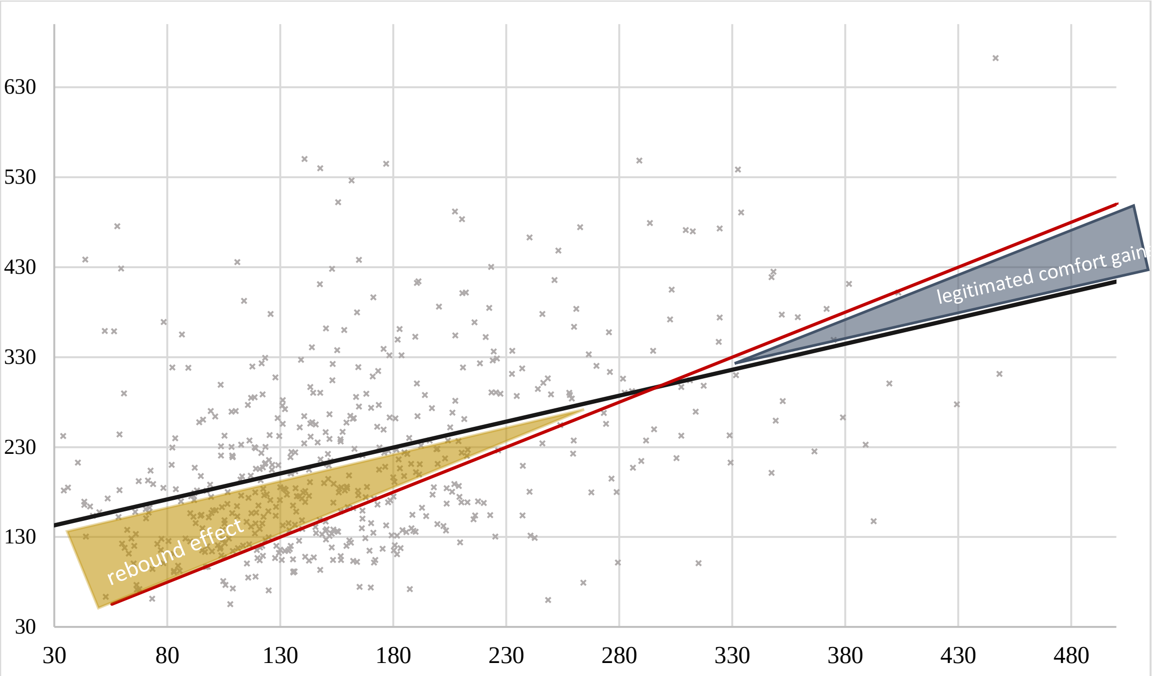
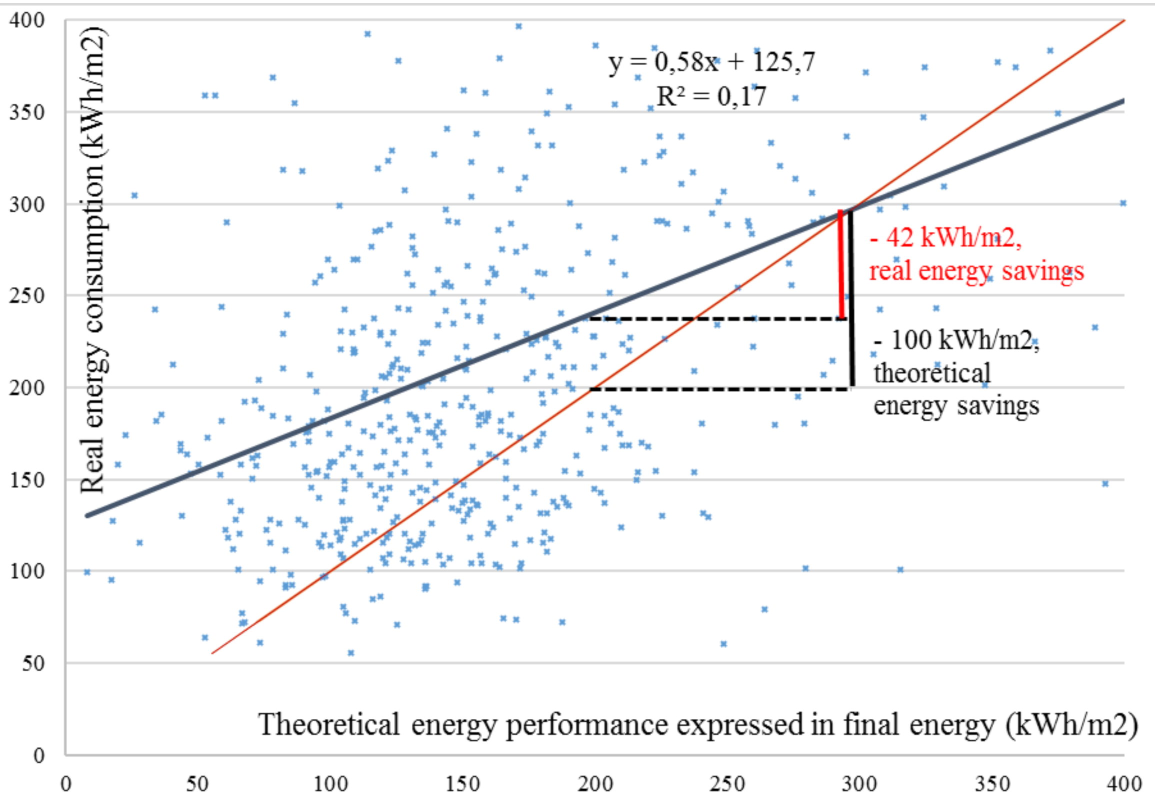


Figure 5b: Measure of rebound effect with cross-sectional dataset



Considerations on fuel poverty and restriction behaviours

Our research demonstrates that under-consumption of energy compared to the theoretical measure is partially explained by poverty and preferences for energy savings over comfort. This consumption pattern is also associated with low energy efficiency in dwellings. Thus, households that under-consume are likely to experience restriction behaviours regarding energy consumption mainly explained by a lack of financial resources to achieve their theoretical well-being standard.

In line with this result, we advise policymakers interested in the fuel poverty issue not to forget the people who restrict their energy consumption. The Grenelle II[10] law defines as fuel poor those people who face difficulties meeting their standard energy needs due to either their low income or their poor living and housing conditions. However, the classic fuel poverty indicator used in France does not identify households restricting their energy consumption as fuel poor; indeed, the measure is based on the ratio of real energy expenditures to income (how much money households are really spending on their consumption of energy relative to their revenue) and not on modelled energy needs. Thus, if a household restricts its energy consumption in comparison to what it should theoretically consume because of financial issues, by design, it will not be considered in the classical energy poverty indicators.

At the national scale, if we assess the mean energy performance gap for the gas-heated dwelling stock (6 million dwellings), we get a mean intensity of energy use of 0.74 (Table 5, sample weights[11]), meaning that in reality, the dwelling stock currently consumes 25% less than estimated by engineering calculations. This could be explained by the dwelling stock's constitution in 2012, when the half of the residential dwelling stock belonged to energy classes less than D and thus are more likely to "under-consume" energy. This result argues in favour of an existing welfare issue regarding thermal comfort for most French households. Future research needs to be done to identify how deep this issue really is.

Table 5

Theoretical energy consumption, gas sample (EPC, kwh)	Real energy consumption (kwh)	IEU
1,21791E+11	90 974 714 580	0,7469752

[10] https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000022470434
[11] Representative of the French housing stock

7. Conclusion

This research provides a new proof of the significant role of individual characteristics in explaining energy consumption variability. Household income, energy price, the number of persons in the dwelling, the age of the reference person, the number of appliances, the number of heating degree days and the preferences for comfort over economy are found to be significant factors in explaining the energy performance gap in the French residential sector. In the specific gas sample, our research highlights that up to 12% of variability in the gap is explained by our variable for individual preferences for comfort.

More than just identifying a list of factors, our research highlights several phenomena that help understand energy consumption patterns in French homes. Firstly, our research demonstrates that under-consumption of energy compared to the theoretical measure is partially explained by poverty issues and preferences for energy savings over comfort. On the other hand, we provide evidence that overconsumption is associated with strong preferences for comfort as well with higher energy efficiency of dwellings. The identification and understanding of these energy consumption patterns are extremely relevant for energy policymaking.

Finally, we would like to stress that a significant share of the energy performance gap remains unexplained or misunderstood, underlying the fact that further research is needed to go deeper into the understanding of extreme performance gaps.

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Appendix

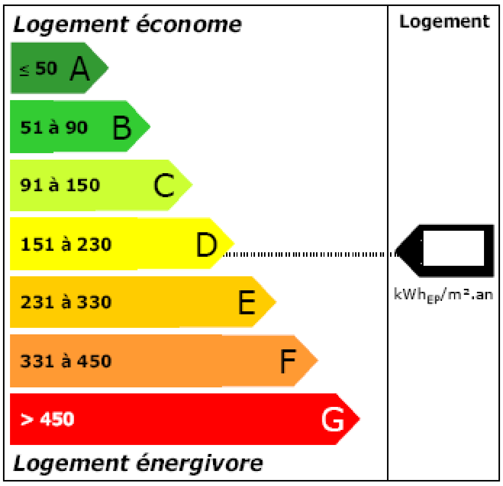
A. Energy class and EPC measure

The increase in comfort demand regarding energy use after an energy-efficiency improvement has been theoretically integrated into the EPC calculation thanks to a factor of intermittence[12] that can be defined as:

$$INT = \frac{I_0}{1 + 0.1\,(G - 1)}$$

where $G = \frac{ENV}{CORH}$ and $CORH = HSP/2{,}5$. ENV is a measurement of the heat losses in the dwelling. I_0 is tabulated data based on heating systems and building type. This INT factor increases with better insulation and thus implies an increase in theoretical energy consumption with the higher energy efficiency of the dwelling. Thanks to the descriptive analysis, we can assume that this factor of intermittence is potentially underestimated in terms of thermal efficiency's effect on energy consumption.

Figure 6: EPC energy classes



[12] This represents the variability of energy consumption due to day-occupancy duration and also includes a kind of rebound effect.

B. Descriptive statistics

Table 6: Stated preferences and behaviour

	Global sample		Gas sample***	
	preference for…*		preference for...	
	Thermal comfort	**Energy-savings**	**Thermal comfort**	**Energy-savings**
Last winter, were you in the habit of regularly lowering the temperature or turning off the heat in the bedrooms …				
At daylight	0.283 **	0.345	0.271	0.354
At night	0 .465	0.517	0.521	0.611
When you open the window to ventilate a room, do you turn the heating of the room down or off?				
Always	0 .374	0.448	0.347	0.441
Most of the time	0.441	0.502	0.438	0.5109
Do you limit your heating consumption?				
Yes	0.090	0 .424	0.097	0.4323
	preference for...			
	Hot water comfort	**Energy savings**		
Number of showers (per cu)	7.137015	7.522		
	preference for...			
	Electricity comfort	**Energy savings**		
Number of appliances	17.08366	15.649		

*"When it comes to indoor heating, do you prefer …?". This question is asked after gathering energy-saving behaviours.
** The null hypothesis of equality of proportions cannot be rejected with a 90% confidence level. All the rest of the proportions are statistically different at the 90% confidence level or more.
***Only preferences for thermal comfort are studied

Table 7: Summary statistics of preferences

	Frequency	%	Frequency	%
No preference	504	27.20	146	28.21
Low preference	393	21.21	111	21.47
Medium preference	412	22.23	111	21.47
Strong preference	544	29.36	149	28.82
Total	1,853	100.00	517	100.00

Table 8: Preferences according to end uses

Whole sample				
	Preference for energy savings - hot water end use		Preference for comfort - hot water end use	
	Preference for energy savings - heating end use	Preference for comfort - heating end use	Preference for energy savings - heating end use	Preference for comfort - heating end use
Preference for energy savings - electricity end use	504	187	158	239
Preference for comfort - electricity end use	48	82	91	544

Gas sample				
	Preference for energy savings - hot water end use		Preference for comfort - hot water end use	
	Preference for energy savings - heating end use	Preference for comfort - heating end use	Preference for energy savings - heating end use	Preference for comfort - heating end use
Preference for energy savings - electricity end use	146	48	48	76
Preference for comfort - electricity end use	15	15	20	149

Table 9: Descriptive statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
Real energy consumption (kwm/m2)	1,853	168.28	95.5	9.72	757.98
Theoretical energy consumption (kwm/m2)	1,853	265.01	134.08	22.52	994.59
Intensity of energy use	1,853	1.06	0.63	0.03	5.29
Intensity of energy use (gas sample)	517	0.83	0.47	0	4.13
Income	1,853	40029	23919	307	249406
Energy price 2012	1,853	0.09	0.03	0.01	0.38
No preference for comfort	1,853	0.27	0.45	0	1
Low preference for comfort	1,853	0.21	0.41	0	1
Medium preference for comfort	1,853	0.22	0.42	0	1
Strong preference for comfort	1,853	0.29	0.46	0	1
Preference for comfort in heating	1,853	0.57	0.5	0	1
Preference for comfort in hot water	1,853	0.56	0.5	0	1
Preference for comfort in electricity	1,853	0.41	0.49	0	1
Heating temperature	1,853	19.93	1.49	8	30
Number of consumption units	1,853	1.69	0.54	1	4.3
Age of reference person	1,853	56.19	15.13	13	98
Cold problem	1,853	0.16	0.37	0	1
Limit heating consumption	1,853	0.23	0.42	0	1
Fuel poor by the 10% definition	1,853	0.1	0.3	0	1
Monetary poor (60% median)	1,853	0.19	0.4	0	1
Renovation work	1,853	0.51	0.5	0	1
Never switch off the heating system	1,853	0.38	0.49	0	1
Adjust the heating system	1,853	0.87	0.34	0	1
Windows closed during heating	1,853	0.01	0.09	0	1
Heating Degree Days	1,853	2496.07	383.01	1285.6	3153.1

Table 10: Ventile of IEU (gas sample), Source: PHEBUS

	Mean	Std. Dev.	Min	Max
1	0.1180	0.0898	0.0000	0.2436
2	0.3181	0.0408	0.2548	0.3683
3	0.4098	0.0219	0.3710	0.4396
4	0.4761	0.0193	0.4442	0.5061
5	0.5219	0.0091	0.5074	0.5373
6	0.5674	0.0151	0.5380	0.5900
7	0.6097	0.0104	0.5901	0.6271
8	0.6476	0.0142	0.6271	0.6687
9	0.6894	0.0128	0.6723	0.7139
10	0.7408	0.0171	0.7153	0.7750
11	0.7952	0.0140	0.7763	0.8154
12	0.8342	0.0122	0.8172	0.8570
13	0.8780	0.0137	0.8575	0.9073
14	0.9296	0.0119	0.9079	0.9490
15	0.9861	0.0224	0.9497	1.0226
16	1.0769	0.0322	1.0289	1.1203
17	1.1787	0.0382	1.1231	1.2534
18	1.3236	0.0389	1.2618	1.3791
19	1.4568	0.0524	1.3804	1.5476
20	2.1234	0.7254	1.5481	4.1300

Table 11: Correlation table

	IEU	Income	No pref	Low pref	Medium pref	Strong pref	Pref heating	Pref HW	Pref elect	Temp (°C)
IEU	1.0000									
Income	0.0862	1.0000								
No pref	-0.0552	-0.1269	1.0000							
Low pref	-0.0514	-0.0392	-0.3171	1.0000						
Medium pref	0.0544	0.0807	-0.3268	-0.2774	1.0000					
Strong pref	0.0504	0.0855	-0.3940	-0.3345	-0.3447	1.0000				
Pref Heating	0.0675	0.1054	-0.7005	-0.0962	0.2282	0.5625	1.0000			
Pref HW	0.0567	0.1052	-0.6853	-0.1618	0.2627	0.5750	0.4323	1.0000		
Pref elect	0.0640	0.1288	-0.5125	-0.3063	0.0077	0.7688	0.4241	0.4611	1.0000	
Temp (°C)	0.1217	0.0304	-0.1819	-0.0168	0.0454	0.1514	0.2420	0.1110	0.1273	1.0000

C. Regressions

Table 12: Robustness tests

	(1)		(2)		(3)		(4)	
	Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85
VARIABLES								
Energy price (log)	-0.0976***	-0.121***	-0.0905***	-0.0993***	-0.0950***	-0.121***	-0.0967***	-0.151***
	(0.0268)	(0.0375)	(0.0233)	(0.0350)	(0.0260)	(0.0368)	(0.0220)	(0.0368)
Income (log)	0.111**	0.106*			0.106**	0.109**		
	(0.0485)	(0.0563)			(0.0496)	(0.0551)		
Uc	0.485*	0.725*			0.470	0.759**	0.0582***	0.0758***
	(0.290)	(0.370)			(0.294)	(0.366)	(0.0180)	(0.0212)
Age	-0.00179***	-0.00212**			-0.00177***	-0.00211**	-0.00169***	-0.00181**
	(0.000660)	(0.000860)			(0.000655)	(0.000847)	(0.000582)	(0.000786)
Heating degree days(log)	-0.107**	-0.324***			-0.109**	-0.322***	-0.110***	-0.286***
	(0.0433)	(0.0693)			(0.0445)	(0.0671)	(0.0385)	(0.0690)
Never switch off the heating system	0.0487***	0.0589***			0.0490***	0.0587***	0.0295*	0.0458*
	(0.0163)	(0.0227)			(0.0161)	(0.0225)	(0.0157)	(0.0249)
Possibility to adjust the heating system	0.0528*	0.00150			0.0503*	0.00196	0.0560**	0.0134
	(0.0279)	(0.0326)			(0.0277)	(0.0343)	(0.0237)	(0.0365)
Windows closed during heating	-0.0675	0.0179			-0.0652	0.0179	-0.0721	0.0125
	(0.118)	(0.156)			(0.120)	(0.162)	(0.122)	(0.162)
Strong preference for comfort							0.0440***	0.0445*
							(0.0142)	(0.0244)
Interaction parameter between income and uc	-0.0373	-0.0895***			-0.0412	-0.0657*		
	(0.0276)	(0.0331)			(0.0277)	(0.0347)		
Constant	0.0802	1.393**	0.253***	0.705***	-0.0366	1.999***	1.027***	2.735***
	(0.615)	(0.705)	(0.0575)	(0.0830)	(0.657)	(0.691)	(0.299)	(0.552)

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1