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Dorothee Charlier, Bérangeère Legendre

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# Carbon dioxide emissions and aging: Disentangling behavior from energy efficiency

Dorothee Charlier\*, Bérangère Legendre†

January 19, 2021

## Abstract

Demographic aging affects Western societies and calls for the adaptation of a number of economic structures. But this trend requires us to take also into account the behavioral changes inherent in aging if we are develop sustainably, specifically concerning resource consumption and carbon dioxide emissions in the context of global warming. The aim of this research is to assess the impact of age on emissions by disentangling the pure effect of behavioral patterns and the effect of home energy efficiency. Showing that a selection bias arises through the choice of home, we isolate the pure effect of the behavior of older people. We use a discrete-continuous model to address potential endogeneity in a residential energy consumption model due to the choice of home energy characteristics. As a key contribution, we provide evidence that age does have a significant but indirect positive impact on carbon dioxide emissions, through the choice of dwelling.

Key words: energy consumption; carbon dioxide emissions; aging; empirical analysis; endogeneity

JEL Codes: Q41, J14

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\*IREGE, Université Savoie Mont Blanc - 4, chemin de Bellevue, 74944 Annecy-le-Vieux, dorothee.charlier@univ-smb.fr

†IREGE, Université Savoie Mont Blanc - 4, chemin de Bellevue, 74944 Annecy-le-Vieux, berangere.legendre@univ-smb.fr

# 1 Introduction

Increasing longevity worldwide is now a well-known phenomenon, and began several decades ago in Europe. The median age in France was 38.6 years in 2000 and is now 41.7 years. In Germany, the average age in 2000 was 40.1 and in 2020 the average age is expected to be 45.7 years. Aging is also particularly striking in Italy, where the average age rose from 40.3 to 47.3 between 2000 and 2020. In 2010, 16.2% of the European population was over 65 years old. In 2017, those over 65 represented 18.2% of the population. Population aging raises questions about how sustainably our societies are developing. Lashof and Ahuja (1990 [29]) showed that greenhouse gas emissions and global warming are closely linked. If age actually increases household energy consumption and carbon dioxide emissions, then the environmental footprint of societies will deteriorate due to demographic trends. Aging is likely to lead to profound changes in energy consumption habits, and therefore in household CO<sub>2</sub> emissions. Indeed, individuals are living longer, leading to changes in household composition and housing choices. Understanding the determinants of residential CO<sub>2</sub> emissions, and particularly those of seniors, therefore appears necessary to construct energy policies. In this paper, we disentangle the emissions that are specifically related to the energy consumption behavior of seniors, after correcting for the selection bias in the choice of housing. The literature reports that older households have a higher demand for electricity and heating, mainly due to daily occupancy time, but also because they have more pronounced preferences for thermal comfort (Brounen et al., 2012[10]; Bardazzi and Pazienza, 2017[3]). Our findings do not agree with previous work: we provide evidence that age does have a significant but indirect impact on carbon dioxide emissions, but only through the choice of dwelling.

Many studies highlight the individual (or household) socioeconomic characteristics that can affect household consumption and greenhouse gas emissions on the one hand and on the other hand the technical characteristics related to housing that also play an important role (Nesbakken, 1999 [35], 2001 [36]) in a micro approach. It is therefore difficult to disentangle the exact determinants of energy consumption and greenhouse gas emissions. Furthermore, many of these characteristics are closely related to the age of individuals, and therefore more broadly to the demographics of a population (Biesiot and Noorman, 1999 [9]; Gatersleben et al., 2002 [21]). The findings of these studies are quite worrying in the context of global warming, which is now well established in the international community. According to Brounen et al. (2012 [10]), demographic changes are undermining the energy savings that can be made in the residential construction sector. They found that the elderly consume more gas for heating than other types of households.

Bardazzi and Pazienza (2017 [3]) summarize the human and non-human factors affecting

the energy consumption of older people. Human factors include behaviors and households and individual attributes, inextricably linked to age. Elderly households are smaller households, leading to a loss of economies of scale (Brounen et al., 2012 [10]). Household size is one of the most important factors influencing per capita energy expenditure and carbon footprint (Longhi, 2015 [31]; Schroder et al., 2015 [42]). According to Longhi (2015 [31]), moving from a one to a two individual household leads to a sharp decrease per capita expenses: by 51% for gas and by 41% for electricity.

Culture is a behavioral attribute reported in the literature to also explain consumption and the environmental footprint of the elderly (Bardazzi and Pazienza, 2017 [3]; Carlsson-Kanyama et al., 2005 [12]; Hamza and Gilroy, 2011 [22]). According to Hamza and Gilroy (2011 [22]), baby boomers have a high demand for domestic thermal comfort, but also for consumables in the home. Consequently they may have less environmentally-friendly attitudes than younger people.

Documenting the impact of demographics Brounen et al. (2012 [10]) provided forecasts of energy demand, taking into account the irreversible aging trend. They emphasized the need to account for the impact of demographic characteristics, especially the growing number of elderly aged 65 or older. In Holland, the number of people older than 65 is expected to double by 2040. Brounen et al. (2012 [10]) showed that energy use will increase, because the elderly consumes more energy for heating than other types of households. They found that the academic literature has neglected the behavioral components of energy consumption, which are directly linked to household demographics, compared with the technical literature. Using item response theory and French micro-data, Belaid and Garcia (2016 [8]) showed that people between the ages 45 and 56 adopt more energy-saving behaviors. Older people tend to prefer energy comfort. In addition, age seems to have a negative impact on environmental behavior which accentuates the difference in behavior between 45 and 56. There is greater behavioral inertia on the part of older people (Hines et al., 1987 [25]).

Housing attributes are “non-human factors” (Bardazzi and Pazienza, 2017 [3]). The period of construction, dwelling type and size strongly influence energy consumption (Brounen et al., 2012 [10]; Meier and Rehdanz, 2010 [32]; Rehdanz, 2007[38]). However, behavior doesn’t explain everything. Today, fuel poverty especially affects a proportion of older people (Legendre and Ricci, 2015 [30]) living in homes whose energy efficiency can be questionable. Poor quality housing therefore has a significant impact on energy consumption, as the literature shows. Many studies also reveal that energy consumption in the home and CO<sub>2</sub> emissions are not independent of the quality of the building characteristics. Brounen et al. (2012 [10]) estimated the impact of the technical characteristics of dwellings and the impact of the demographic attributes of households on the consumption of gas and electricity separately and then devel-

oped models combining both. This overlooks the notion that housing choice is probably not independent from individual and household attributes, including demographics.

Some of the existing work raises the question of the exogeneity of the technical characteristics of housing. Thus, one of the contributions of our research is to take this important assumption into account. Indeed, Durbin and McFadden (1984 [18]) concluded that households choose their housing according to its characteristics. Durbin and McFadden (1984 [18]), Nesbakken (1999 [35]; 2001 [36]) and Vaage (2000 [43]) assumed for example that appliance or heating system choices and consumption choices are bound. Age could play a twofold role in explaining CO<sub>2</sub> emissions: first, it influences the choice of home characteristics or appliances (indirect effect on CO<sub>2</sub> emissions); second, once the appliances or home characteristics are considered, age also has a direct influence through consumption behavior. Estiri (2015 [19]) concluded that 80% of the effects of household socioeconomic characteristics are observed via building characteristics.

The physical attributes of dwellings can therefore no longer be considered to be exogenous variables in explaining energy consumption and greenhouse gas emissions. Methodologically, this raises the question of the selection bias in the studies cited above. In choosing housing according to its characteristics, households self-select, then adopt a consumption pattern that is known to be directly influenced by their age. They therefore make a two-step decision. We can then consider that there are determinants impacting housing demand, but not energy consumption or domestic emissions. Technically, this requires finding robust instrumental variables that allow an appropriate methodology to be implemented. The framework of conditional demand analysis employing the two-step discrete-continuous model first put forward by Durbin and McFadden (1984 [18]) has been used to model energy consumption. Using these models, researchers address selectivity biases in data sets with endogenously partitioned observational units (Bakaloglou and Charlier, 2019 [1]; Frondel et al., 2016 [20]). These models are thus often used in the field of energy consumption due to the interactions and endogeneity between independent explanatory variables. Identifying good instruments with sufficient explanatory power is extremely difficult, which may explain why existing research favors a single model or two different econometric models to highlight the human and non-human determinants of energy consumption and greenhouse gas emissions.

When studying demographic aging, there are three temporal dimensions : the age of individuals, the period in which the analysis is anchored and the cohort to which the individuals belong (Chancel, 2014 [14]). In the present study, we adopt an age approach to focus on the impact of age on CO<sub>2</sub> emissions and thus draw conclusions to build an energy policy based on observations over a recent period. To do so, we use the PHEBUS survey, conducted by the

French Ministry of Ecology and Sustainable Development. The survey provides cross-sectional annual data (2012), thus enabling an age-based approach.

We then fill the gap in the literature by disentangling the impact of age on housing characteristics, and the impact of age on behavior. We aim to correct for selection bias in the impact of age on energy consumption, which is overlooked in the literature. Based on the existing energy consumption literature, the main assumption of this study is that age has a significant but indirect positive impact on CO<sub>2</sub> emissions. We assume that the household's decision is divided into two parts. In the first, the household decides to live in a housing unit according to its theoretical energy/climate performance (depending on its technical characteristics). In the second, it decides how much energy to consume according to the occupants' age. Properly disentangling these aspects, particularly by correcting for selection bias and the effect of age on dwelling choice and consumption will be of great help in designing energy policy relevant to aging societies. Our results differ from the conclusions of previous studies. They shed new light on the impact of age on CO<sub>2</sub> emissions and thus on the impact that aging could have on global warming. We find that each additional year of life increases theoretical CO<sub>2</sub> emissions from 0.0041 to 0.0044kg per square meter, but does not have an impact on effective CO<sub>2</sub> emissions. We thus provide evidence that age does have a significant but indirect impact on carbon dioxide emissions, through the choice of dwelling. The dataset is presented in Section 2. Section 3 sets out the empirical strategy. The results and discussion are presented in Section 4, and Section 5 concludes.

## 2 Data

### 2.1 Data and Variables

#### The survey

In the present study we use the PHEBUS survey, conducted by the French Ministry of Ecology and Sustainable Development. This national household survey is made available by the Ministry's Department of Observations and Statistics (SOeS). Energy audits performed in 2012 on 2,040 individual dwellings are reported, providing enough data to study theoretical energy-efficiency and actual energy consumption (based on energy bills). In fact, all the technical characteristics (insulation, appliances, etc.) that form the basis of the Energy Performance Certificate (EPC) are provided. Professionals were thus able to provide an accurate assessment of theoretical emissions. Social, economic and behavioral variables of the occupants are also recorded.

The survey provides cross-sectional annual data (2012) and is representative of the French

dwelling stock according to region, climate zone, dwelling type and building construction date. The survey was conducted using face-to-face interviews. The richness and originality of the database lie in the information contained in the EPC, collected through audits. An independent auditor visited dwellings to collect technical data and evaluate the theoretical CO<sub>2</sub> emissions calculated from engineering models with the assumption of standardized behaviors. The mode of data collection, the expertise of the auditors and the precision of the information collected about the energy attributes of the dwelling make this survey a unique source of data for researchers. Very few surveys provide this level of detail on dwellings and at the same time on the socioeconomic characteristics of the inhabitants. The survey also includes behavioral questions.

### **Theoretical and effective carbon dioxide emissions**

The energy audit will draw up a balance sheet of the energy losses of the dwelling and makes it possible to establish the theoretical CO<sub>2</sub> emission of the dwelling and the EPC. Indeed, according to the literature, technical building characteristics (insulation, year of construction, appliances, energy mix) can account for more than half of the energy consumption/CO<sub>2</sub> emissions variability in the residential sector (Baker and Rylatt, 2008 [2]; Estiri, 2015 [19]; Harold et al., 2015 [23]; Risch and Salmon, 2017 [39]). Newer buildings tend to consume less energy due to energy efficiency measures (Koirala et al., 2013 [26]). Such improvements are as a result of changes in building codes and construction techniques. Theoretical CO<sub>2</sub> emissions are estimated using the 3CL method<sup>1</sup>:

$$CO_2 = CO_{2ch} + CO_{2ecs} + CO_{2cool} \quad (1)$$

Where  $CO_{2ch}$  is the theoretical heating CO<sub>2</sub> emissions of the dwelling,  $CO_{2ecs}$  the theoretical CO<sub>2</sub> emissions for hot water use and  $CO_{2cool}$  the theoretical CO<sub>2</sub> emissions for cooling use.

The main assumptions in the calculation are as follows. The EPC depends on building insulation, appliances, dwelling characteristics and location as well as the energy mix. The EPC depends on building insulation, appliances, dwelling characteristics and location as well as the energy mix. The meteorological data used are the heating degree hours of the département (county) of reference to assess the heating needs of the building. Although France is not a geographically large country, there are significant differences in climate between coastal areas,

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<sup>1</sup>This method, known as 3CL for "Calculating Conventional Housing Consumption", was established in 2006 to incorporate the 2002 European directive on the energy performance of housing into French law. Since 2007, the energy performance diagnosis (DPE) has been a mandatory part of every deed of sale. The level of energy performance of the homes is evaluated in relation to average usage and climate data, according to a set of conventions.

mountainous areas and areas with a more continental climate. Therefore, we take into account the administrative division of the country by integrating differences by département. 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 to be heated permanently during the heating season. Moreover, hot water needs are set according to the habitable area and the département where the dwelling is located. Ultimately this engineering calculation provides the theoretical CO<sub>2</sub> emissions for each dwelling, expressed in kg CO<sub>2</sub>. This method thus makes it possible to classify the dwellings by energy label<sup>2</sup>, ranging from the rank A for the best performing dwellings to the rank G for the most inefficient dwellings (see Figures 5 and 6 in the appendix). It is also a way to estimate effective CO<sub>2</sub> emissions by controlling for theoretical characteristics (see Figure 7 in the appendix).

### **Actual carbon dioxide emissions**

Information on actual CO<sub>2</sub> emissions for each dwelling is also available in the PHEBUS survey using actual energy consumption and applying a conversion factor. Information on actual energy consumption collected is based on households' detailed invoice and is available for each type of fuel in kilowatt hours and is also converted to tonnes of oil equivalent. Actual energy consumption is expressed in kilowatt-hours per square meter and it is based on energy bills for the year 2012. It includes all energy consumption, regardless of the energy uses. To compute CO<sub>2</sub> emissions, we used common energy consumption in kilowatt hours according to each type of fuel and applied the conversion factor for 2012 to obtain CO<sub>2</sub> emissions in kg<sup>3</sup>. GHG emissions from the residential sector calculated during energy performance audits include direct emissions from housing, i.e. those related to the combustion of fossil fuels (fuel oil, natural gas) by individual and collective boilers, cooking appliances or water heaters. Energy sources in French dwellings mainly include electricity (31%), gas (40%), domestic fuel (16%), wood (3.5%) and district heating (5%).

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<sup>2</sup>Theoretical emissions are calculated from the theoretical primary energy consumption. Primary energy is the "potential" energy contained in natural resources (such as wood, gas, oil, etc.) before any transformation. Final energy is the energy consumed and charged to each building, taking into account losses during the production, transport and transformation of the fuel. In the heating latest regulation RT 2012 for buildings, the results are detailed as primary energy. This has the advantage of being able to better compare the different energies between them. Apart from electrical energy, the conversion rate of all other energies is 1 (primary energy = final energy). For electricity, 1 kWh in final energy is equivalent to 2.58 kWh in primary energy. This conversion rate, normalized, has been calculated taking into account the average efficiency of electricity production in power plants in France, which is 43.5%, as well as the losses during distribution, which are 5%. This gives an electricity production efficiency of 38.5%, hence the coefficient 2.58.

<sup>3</sup>The typical conversion factors are 0.09 for electricity, 0.206 for gas, 0.271 for oil, 0.343 for coal and 0.0018 for wood (IPPC, 2013); 0.09 kg of CO<sub>2</sub> for 1 kilowatt hour of electricity consumed.



## **Household characteristics, preferences, and length of occupancy**

We used income, number of persons, gender, length of occupancy, the number of days of housing vacancy during the heating season, and the behavior of occupants as the main controls for household characteristics. The effect of income elasticity is positive in most studies. This is consistent with the "normal good status" of energy consumption: income elasticity often lies between 0.01 and 0.15 (Bakaloglou and Charlier, 2019 [1]; Cayla et al., 2011[13]; Labandeira et al., 2006[28]) (Charlier and Kahouli, 2019 [15]; Nesbakken, 1999 [35]; Santamouris et al., 2007[40]). Studies also seem to show that gender has an effect on emissions: men consume more energy (Barla et al., 2011 [4]; Bel and Rosell, 2017 [6]). Moreover, information on stated household behavior is available from the PHEBUS survey. For each behavior (opening windows during the heating season, turning off the heating when unoccupied, etc.), a binary variable makes it possible to know whether the household stated having the behavior or not. It is possible also to obtain some information about heating preferences. Households answered the following question: "When it comes to heating, do you give priority to comfort or saving energy?".

## **Energy prices**

Price elasticity is always found to be negative, but estimates vary widely from -0.20 to -1.6 depending on energy type, methodology used, level of aggregation of data, evaluation method, country, etc. (see the meta-study of Labandeira et al., 2017 [27] which is based on 428 papers). The PHEBUS database does not provide energy price information directly but provides information on the type and amount of energy consumed by each dwelling according to each type of fuel, and also on the type of contract (for gas and electricity) and the power required per type of fuel used in kVA (electricity, gas, oil). The power required depends on the type of fuel used for the heating system (i.e. the energy mix) as well as the number of rooms (or the surface area) and the number of appliances. Therefore, using the information in the database, we can assume what type of tariff that households have. Finally, the PHEBUS data set also provides information on the quantity consumed in peak hours and in off-peak hours <sup>4</sup>. Thus, to complete the PHEBUS data set, we looked at the PEGASE database (provided by the French Ministry of Energy, see Table 7 in the appendix) to obtain the energy and subscription cost for each type of electricity and gas per the amount of power required and the type of contract in 2011 and 2012.

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<sup>4</sup>The average CO<sub>2</sub> content calculated in this paper does not take into account the variability of the CO<sub>2</sub> content of the kWh according to the seasons or time of day. However, this value evolves according to the level of electricity consumption, depending on end uses.

## Climate data for 2012 - unified degree days

As explained above, the dataset also provides the département where each dwelling is located. This information was matched with 2012 meteorological data from Météo France (annual heating degree days by département) in order to obtain a proxy for the actual 2012 meteorological conditions and to control for different climates within the same country. As theoretical CO<sub>2</sub> emissions (based on the EPC) integrates climate data from the past 30 years, using the actual heating degree days for 2012 is assumed to influence the gap between theoretical CO<sub>2</sub> emissions and effective CO<sub>2</sub> emissions. This variable is decisive since it would make it possible to understand significant differences between theoretical and actual emissions over a year. Narayan and Smyth (2005[34]), using aggregate time series data, showed that residential electricity demand in Australia notably depends on the number of heating-degree and cooling-degree days. In the absence of information about cooling-degree days, a proxy for air conditioning is considered.

## 2.2 Descriptive statistics

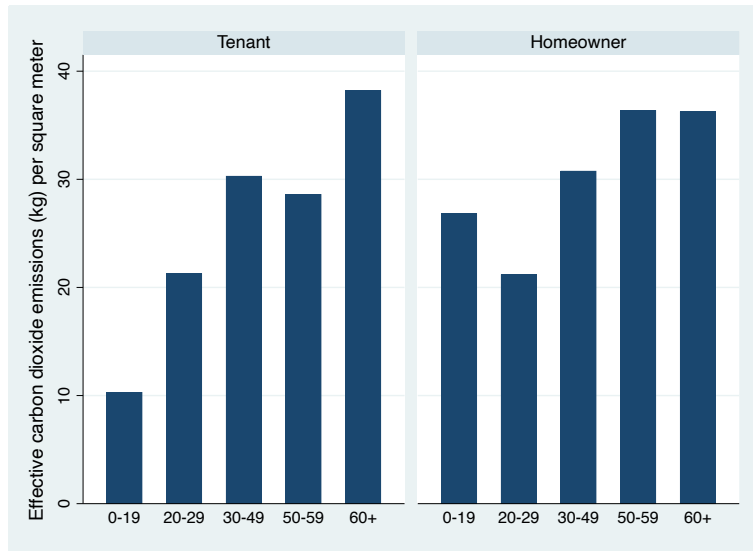
The main descriptive statistics are provided in Table 1. The average age in the sample is 56 years old. This average age is based on the average age of heads of household, i.e., minors are excluded from the analysis. As a result, the average is higher than the national average, but if we calculate the average over the entire sample, taking into account the age of the children, we drops to 41 years (which is the national average age). As a result, there is no representativeness problem in the sample. There were very few households residing in Label A dwellings in 2012, with a significantly higher concentration in Labels C, D and E: 19%, 21% and 20% respectively. The least energy efficient labels, F and G still accounted for 23% of the sample. These statistics remain consistent with those in the distribution by construction period where the distribution is similar. 87% of households had a thermostat, and only 8% of households had air conditioning. Households owned an average of 15 appliances and were absent from their dwelling for one week per year. A further 16% reported being cold due to heating restrictions, 13% open windows when the heating is on, and almost a third never turn off the heating.

To examine the relationship between average age and occupancy status (the dwellings that consume the most energy are often inhabited by tenants). we look at average emissions by age group and occupancy status (Figure 1). Although renter households aged 60 and over consume slightly more on average than owners. there is no marked contrast between the two occupancy statuses. If we look specifically at the distribution of households according to age for the different climate labels (Figure 2). it is quite clear that the average age is higher in dwellings with a higher emissions profile (results reinforced in Tables 2 and 3). The mean age in the sample is 56.08.

Table 1: Descriptive statistics

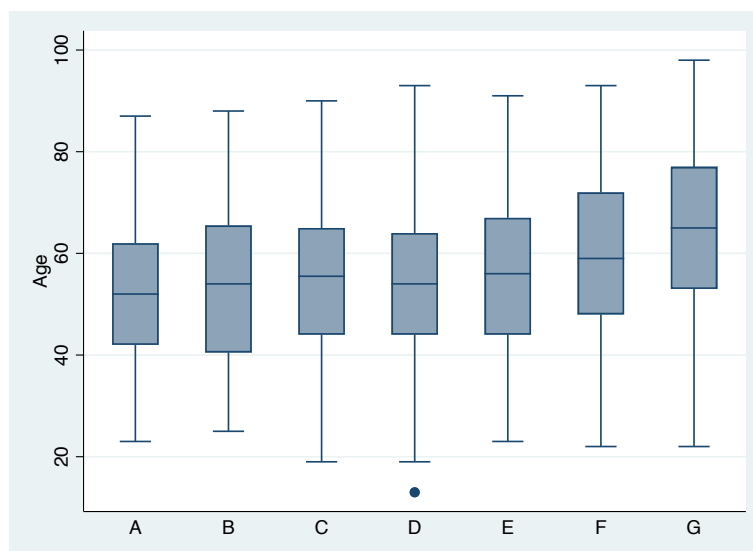
VARIABLES	N	mean	sd	min	max
Effective CO <sub>2</sub> /m <sup>2</sup>	2009	33.788	33.475	0.746	739.8421
theoretical CO <sub>2</sub> /m <sup>2</sup>	2009	38.701	32.201	0.71	344.61
Disposable income (euros)	2009	40472	24648	3244	277601
Age	2009	56.086	15.201	13	98
Number of persons	2009	2.54	1.288	1	10
Unified Degree Days	2009	2342.69	705.08	0	3153.1
Male	2009	0.701	0.458	0	1
Electricity price (in euros)	2009	0.024	0.032	0	0.0939
Gas price (in euros)	2009	0.136	0.029	0.0652	0.416
Climate label (labels)					
A	2009	0.066	0.249	0	1
B	2009	0.104	0.305	0	1
C	2009	0.192	0.394	0	1
D	2009	0.21	0.407	0	1
E	2009	0.202	0.402	0	1
F	2009	0.124	0.330	0	1
G	2009	0.102	0.303	0	1
Period of construction					
Before 1919	2009	0.167	0.373	0	1
1919-1945	2009	0.092	0.289	0	1
1946-1970	2009	0.172	0.377	0	1
1971-1990	2009	0.328	0.469	0	1
1991-2005	2009	0.176	0.381	0	1
After 2006	2009	0.066	0.249	0	1
Thermostat	2009	0.867	0.34	0	1
Air conditioning	2009	0.079	0.27	0	1
Number of appliances	2009	14.976	5.872	1	55
Rural	2009	0.274	0.446	0	1
2.000 to 4.999 inhabitants	2009	0.094	0.291	0	1
Vacancy period (days)	2009	6.829	45.608	0	999
Cold problem due to heating restriction	2009	0.161	0.368	0	1
Open windows during the heating season	2009	0.135	0.342	0	1
Do not turn down the heating (windows open)	2009	0.277	0.448	0	1
Never turn down the heating (windows open)	2009	0.329	0.47	0	1
Never turn down the heating during periods of inoccupancy	2009	0.114	0.318	0	1

Figure 1: Effective carbon dioxide emissions, age and housing occupancy status



Source : PHEBUS Survey, 2012

Figure 2: Climate label category and mean of age



Source : PHEBUS Survey, 2012

Table 2: Age and energy consumption variables

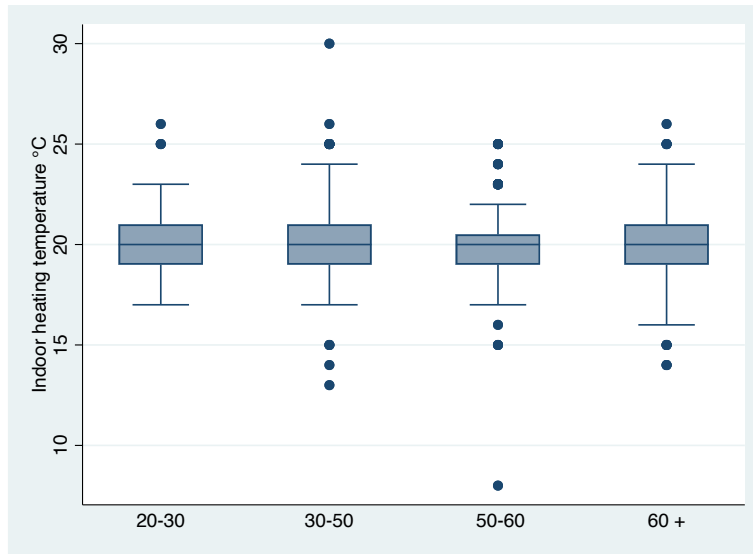
	N	Age		T-test
		Mean	Std. Dev	t
<b>Building characteristics</b>				
Period of construction				
Before 1919	335	57.14	0.91	-1.39
1919-1945	184	55.19	1.17	0.86
1946-1970	345	59.20	0.87	-4.19 ***
1971-1990	658	59.29	0.53	-6.67 ***
1991-2005	354	50.47	0.68	7.77***
After 2006	133	45.71	1.10	8.28 ***
<b>Climate label</b>				
A	133	51.97	1.16	3.24 **
B	208	53.72	1.03	2.37 **
C	386	54.68	0.74	2.03**
D	421	54.35	0.71	2.62**
E	406	55.90	0.74	0.28
F	250	59.38	0.99	-3.66***
G	205	63.71	1.13	-7.69***
Detached house	1,131	58.35	0.42	-7.68***
Not a detached house	878	53.17	0.54	
<b>Location</b>				
Rural	550	55.60	0.40	-2.34**
2,000 to 4.999 inhabitants	188	54.47	1.05	1.53
5.000 to 9.999 inhabitants	78	57.81	1.60	-1.02
10.000 to 19.999 inhabitants	139	55.08	1.32	0.81
20.000 to 49.999 inhabitants	159	55.91	1.25	0.15
50.000 to 99.999 inhabitants	114	54.88	1.45	0.87
100.000 to 199.999 inhabitants	107	55.81	1.59	0.19
200.000 to 1.999.999 inhabitants	487	56.43	0.70	-0.57
Paris	187	54.07	1.13	1.90*

Table 3: Age and energy consumption variables

	N	Age		T-test
		Mean	Std. Dev	t
<b>Appliances</b>				
Portable air conditioner	159	56.56	1.15	-0.41
No portable air conditioner	1850	56.04	0.35	
Thermostat	1742	56.93	0.36	0.98
No thermostat	267	55.96	0.99	
<b>Behavior and preferences</b>				
Preference for thermal comfort	1138	56.11	0.46	-0.09
No preference for thermal comfort	871	56.05	0.50	
Cold problem due to heating restriction	324	53.11	0.85	3.86
No cold problem due to heating restriction	1685	56.66	0.37	
Open windows when the heating is on	271	53.49	0.96	3.03***
Do not open windows when the heating is on	1728	56.49	0.36	
Do not turn down the heating when windows are open when windows are open	557	57.27	0.66	-2.17**
Turn down the heating when windows are open	1452	55.63	0.40	
Never turn down the heating when windows are open	661	55.60	0.62	0.99
Turn down the heating	1348	56.32	0.41	
Never turn down the heating during periods of inoccupancy	230	53.31	1.03	2.96***
Turn down the heating during periods of inoccupancy	1779	56.45	0.36	

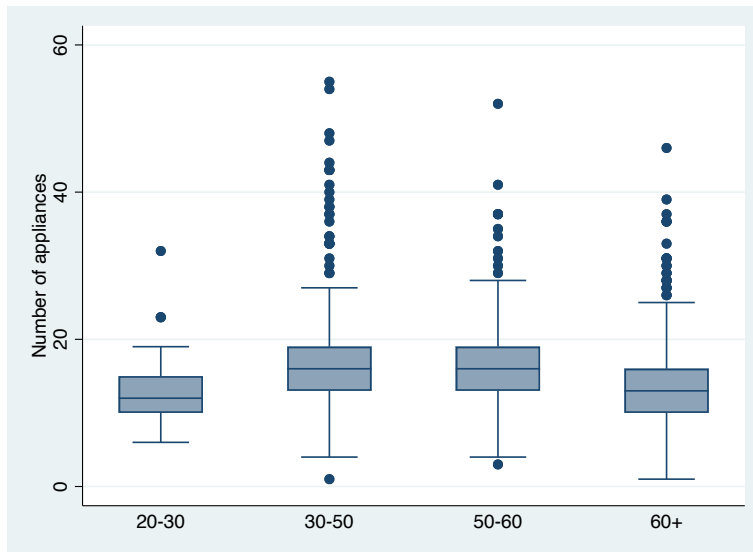
In Tables 2 and 3, we identify differences in average age between different population groups. When the variables are categorical, for each modality, we compare the mean of the modality to the mean of all other modalities. When the variable is binary discrete, we compare the mean from one group to the other group. Our discriminant variables are building characteristics (period of construction, climate category, type of housing, energy efficiency), location, appliances (air conditioning and thermostat), preferences for thermal comfort, heating restriction and behavior during the heating season. What is clear is differences are mainly in average age by building type and location (especially in rural areas) and there are no differences in average age by type of behavior. From a descriptive point of view, it does not appear that people having a preference for thermal comfort are older. Neither do they adopt behaviors that result in more emissions. On the contrary, we even find that people who turn off the heating when windows are open are slightly older on average. The same observation is made for closing the windows when the heating is on.

Figure 3: Indoor stated heating temperature in winter by age class



Source : PHEBUS Survey, 2012

Figure 4: Number of appliances by age class



Source : PHEBUS Survey, 2012

This result is corroborated in Figure 3. It is clear that the average stated winter heating temperature in dwellings is the same regardless of age group. Older people do not seem to have a stronger preference for thermal comfort. People older than 60 are also less likely to own appliances than people aged 30 to 60 (Figure 4). This higher rate of appliance ownership for the 30 to 60 age group may be explained by the presence of children in the household. These descriptive statistics suggest that the potential impact of age on energy consumption

and greenhouse gas emissions (Figure 2) does not operate via the specific consumption behavior of older people (Figures 3 and 4). Therefore, further investigation is needed to understand the channels by which age affects consumption and emissions.

## 3 Model

### 3.1 Theoretical background

Endogeneity occurs when a variable, observed or unobserved, that is not included in our models, is related to a variable we incorporated in our model. In this paper, we confront one potential problem of endogeneity related to theoretical energy performance. Households do not consume energy and emit as an end in itself, rather energy provides utility indirectly through the use of heating systems and appliances. The process of carbon dioxide emissions could be described as a two-step process. First, households choose their theoretical carbon dioxide emissions which can be measured as a result of a combination of the stock of appliances and the type of fuel used for the main end uses (heating and hot-water). Second, they decide how much energy to consume given the available technology and the main fuel used in the dwelling (relating to preferences for thermal comfort for example). This leads to a potential endogenous problem of theoretical carbon dioxide emissions and we have to take this into account to obtain unbiased results.

For several decades, conditional demand analysis employing the two-step discrete-continuous model initiated by Durbin and McFadden (1984[18]) has been used to model energy consumption<sup>5</sup> and to deal with this source of endogeneity. In discrete-continuous models, researchers assume that appliance or heating system choices and consumption choice are bound (Durbin and McFadden, 1984[18]; Risch and Salmon, 2017 [39]; Vaage, 2000 [43]) and use these models to address selectivity biases in data sets with endogenously partitioned observational units (Fron del et al., 2016 [20]). In using these approaches, researchers assume the existence of implicit choices and preferences in terms of home characteristics or energy appliances and their effects on energy consumption. These models are thus often used in the field of energy consumption due to the interactions and endogeneity between independent explanatory variables. Models using the discrete-continuous framework assume that age could play a twofold role in explaining CO<sub>2</sub> emissions: first, it influences the choice of home characteristics or appliances (indirect effect on CO<sub>2</sub> emissions); second, once the appliances or home characteristics are considered, they also have a direct influence, all things being equal. Considering that energy consumption and emissions are bound, we apply the same methodology to deal with the po-

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<sup>5</sup>Modeling energy consumption is similar to modeling CO<sub>2</sub> emissions in that the latter is derived from energy consumption



tential endogeneity.

Recently, there has been interest in examining the issue of interactions. For instance, Estiri (2015 [19]) called attention to the major interactions between building characteristics and life-cycle and socioeconomic household characteristics. He concluded that the main effects of socioeconomic and life-cycle characteristics are observed via building characteristics (expressed with a latent variable that includes surface area, number of rooms, and tenure status). In the same vein, Belaid (2017 [7]) employed a structural equation modeling approach (PLS approach) using French data to determine the indirect role of household characteristics on building characteristics in order to explain residential energy consumption. Both examples allow overcoming the limits identified in previous papers but not treated methodologically. For example, Brounen et al. (2012 [10]) emphasized that “the energy consumption of the elderly [...] is highly responsive to thermal quality of homes as reflected in period of construction” but do not control for the endogeneity of age or period of construction.

Here, we estimate effective CO<sub>2</sub> emissions conditional on housing choice based on energy efficiency determined by theoretical CO<sub>2</sub> emissions. Using a continuous variable instead of a discrete variable to determine household choices is a distinct advantage. It allows us to confirm the econometric quality in this initial step, by adopting traditional parametric statistics tests. The main assumption of this research is that age has a significant indirect but positive impact on CO<sub>2</sub> emissions. We assume that the household’s decision is divided into two parts. In the first, the household decides to live in a housing unit according to its theoretical energy/climate performance and in the second, it decides how much energy to consume according to age. To test this hypothesis, we used an endogenous choice model framework to account for the assumed interactions between household characteristics and the dwelling’s energy-efficiency level. The specification of household fuel emissions is based on a utility model with R\* the stochastic indirect utility function of the households, which we assume to be unobserved. This specification is derived from Bakaloglou and Charlier (2019[1]). Indirect utility V depends on the price of energy P, income Y, household characteristics (including age) and behavior/preferences Z and building characteristics (including location) W and is defined conditionally on the choice of climate performance. Therefore:

$$R_{ij}^* = V_{ij}[P_i, Y_i, Z_i, W_i] + \nu_{ij} \quad (2)$$

where  $j$  is the energy performance,  $N$  that of the individuals, and  $\nu_{ij}$  the error term. The Roy’s identity gives us the household’s Marshallian demand/emission function for energy:

$$X_{ij}(P_i, Y_i, Z_i, W_i) = \frac{\partial V_{ij}[P_i, Y_i, Z_i, W_i]/\partial P_j}{\partial V_{ij}[P_i, Y_i, Z_i, W_i]/\partial Y_i} \quad (3)$$

When simplified, the energy/emissions demand function conditional on climate performance  $j$  by household  $i$  can be written as follows:

$$q_{ij} = \gamma_{ij}z_{ij} + \nu_{ij}w_{ij} + \beta_{ij}P_{2012i} + \eta_{ij} \quad (4)$$

where  $q_{ij}$  is the quantity of greenhouse gas emissions by household  $i$  according to climate performance  $j$ ,  $z_{ij}$  is a vector of household characteristics (including age, income, number of persons and behavior),  $P_{2012i}$  is the energy price,  $w_{ij}$  is a vector of building characteristics (including location),  $\gamma_{ij}$  and  $\nu_{ij}$  are vectors of the related parameters, and  $\eta_{ij}$  the error term taking into account the influence of unobservable parameters.

### 3.2 Econometric methodology: an endogenous choice

In our research, an original data set was used to consider the potential problem of endogeneity related to the choice of the dwelling's thermal performance. As a choice variable, we used the theoretical climate performance of the dwelling according to the theoretical climate certificate (continuous variable). Thus, we studied which characteristics determine the choice of a theoretical energy-efficient dwelling. Using this information in the first step, enables us to capture interactions between energy efficiency and households while identifying direct drivers of CO<sub>2</sub> emissions. Thus, for the first stage, we use a simple regression. For individual  $i$ , we specify:

$$qt_{ij} = \gamma_{ij}z_{ij} + \nu_{ij}w_{ij} + \beta_{ij}P_{2012i} + ELEVATOR_{ij} + LENGTH_{ij} + \eta_{ij} \quad (5)$$

where  $qt_{ij}$  is the theoretical CO<sub>2</sub> emissions of a dwelling  $j$  for households  $i$ ,  $z_{ij}$  is a vector of household characteristics (including age, income, number of persons and behavior),  $P_{2012i}$  is the energy price in 2011,  $w_{ij}$  is a vector of building characteristics (including location),  $\gamma_{ij}$  and  $\nu_{ij}$  are vectors of the related parameters, *ELEVATOR* and *LENGTH* are variables used as instruments and  $\eta_{ij}$  the error term taking into account the influence of unobservable parameters.

In order to obtain a proxy for theoretical CO<sub>2</sub> emissions, an instrument should be identified that explains the environmental performance or obsolescence, but not the actual emissions (conditional on theoretical emissions). The choice of these instruments is mostly founded on the following assumptions. In addition after presenting the intuitive evidence, we will bring some empirical proofs in the next section that these two instruments seem to be good instrument.

To confirm the presence of endogeneity in the choice of housing, we considered instruments that can measure housing obsolescence, environmental performance and potential energy leakage not directly measured by construction periods. The presence of an elevator can explain the theoretical emissions (the choice of a more or less energy-efficient dwelling): over-consumption

in ground and top floors is mostly subjected to vertical heat losses. In buildings there are horizontal and vertical heat transfers and households's choices can consider these heat losses (Najjar et al. 2019 [33] ) when they choose their dwelling. The presence of an elevator may explain the choice of accepting to live on a high floor because it will be more convenient, in view of an unobserved health condition, to go upstairs, run errands or have young children with a pram. The presence of an elevator can also have the opposite effect, as the household does not wish to pay collective charges for the maintenance of the elevator and will prefer a dwelling on a ground floor. From an intuitive point of view, the most recently built dwellings are those equipped with an elevator. The most recent buildings are equipped with an elevator. But there are also elevators in buildings. There is some heat loss in multiple occupancy housing depending on insulation, height, number of floors and number of units . By carrying out a dependency test between the construction period and the presence of an elevator, we can see that there is a dependency between the two variables ( $\chi^2$  test significant at 1%). Elevators are over-represented in recent housing. Going further, we see that on average (mean comparison test) there is a significant difference in average energy consumption between buildings with and without elevators. Units without elevator consume in average  $+36.9kWh/m^2$ . In an opposite way, there is independence between the existence of an elevator in the building and the preference for thermal comfort. These different arguments, and the existence of an elevator, will therefore not explain the household's heating consumption, but may explain the choice to live in a multi-family building with an elevator. Thus, the presence of an elevator has no reason to have an impact on real consumption behavior, and therefore real emissions, except indirectly through the theoretical energy efficiency of the dwelling.

The duration since move-in is an instrument that allows us to measure the obsolescence of the units considering that this instrument is a proxy of period of construction but also enables us to consider a potential energy efficiency renovation in the past. Indeed, we use the duration since move-in because a household that moved into a dwelling two decades ago does not live in a recently built dwelling. It is possible that a dwelling has been renovated when a household has lived in it for a long time. In the survey, energy performance diagnosis consider past renovations. Nesbakken (2001 [36]) uses the capital depreciation rate as an instrument explaining the choice of technology in the endogeneity control stage. Here, we can therefore draw a parallel with the duration of moving in as an explanation of theoretical efficiency. The longer this duration is, the greater the depreciation can be, given that the effect of renovations is controlled in the diagnosis. It is possible that in old dwellings, those that have been lived in for a long time, households may have changed their heating system, which often has a lifespan of 10 years, or put in double glazing. Turnover rates can reflect past decisions to renovate in order to enjoy the benefits of energy saving renovation. It can be assumed that a household

that moved in a long time ago and planned to stay in the same dwelling for a long time would consider energy retrofits more readily than a household that stayed for a short period of time, due to uncertainty about the return on investment. Uncertainty about the return on investment is a commonly identified factor explaining a low rate of investment in energy efficiency (Dixit and Pindyck 1994 [16]; Henry 1974 [24]; Pindyck 1991 [37]). As a result, this indicator takes into account not only obsolescence related to the construction period but also any renovations that have taken place since the date of the survey. By performing an average comparison test, we see that people who have been in their home for a long time renovate more than others on average. There is a positive and significant correlation between having carried out work within four years and the length of occupancy. There is also the correlation between the theoretical emissions and the duration since move-in. This could also be true if one goes back further in time and therefore affects theoretical emissions. Finally, there is independence between duration since move-in and preferences for thermal comfort using a comparison test of means. There is no difference in average duration since move-in according to declared preferences. Households who declared preferences for thermal comfort have an average duration since move-in of 18.6 years against 17.89 for households who have preferences for energy savings.

Theoretical CO<sub>2</sub> emissions are also introduced in the second equation (the second stage) and used as regressors of effective CO<sub>2</sub> emissions with other explanatory variables. The model captures the possibility of correlation between unobservable variables in both stages. Conditional on the first stage, a household decides on the quantity of CO<sub>2</sub> emissions to emit (derived from energy consumed). Therefore, in the second stage, the total CO<sub>2</sub> is estimated, conditional on the dwelling's thermal performance (EPC) and a set of explanatory variables (energy price, income, individual behavior, housing characteristics, etc.). This is the *CO<sub>2</sub> emission choice*.

We therefore have:

$$q_{ij} = \gamma_{ij}z_{ij} + \nu_{ij}w_{ij} + \hat{q}t_{ij} + \beta_{ij}P_{2011i} + \epsilon_i \quad (6)$$

where  $q_{ij}$  is the final effective CO<sub>2</sub> emissions per square meter consumed,  $\hat{q}t_{ij}$  the predicted theoretical CO<sub>2</sub> emissions and  $z_{ij}$ ,  $w_{ij}$  the regressors and  $P_{2011i}$  the energy prices (gas and electricity prices) in 2011 <sup>6</sup>. An interaction parameter is also introduced between both prices to control for multicollinearity. We estimate the model using a maximum likelihood estimator (compared with a two-stage least-squares model). Evidence that using a maximum likelihood estimator is better than a two-stage least squares (2SLS) method is provided in next section. A system composed of the two simultaneous equations (5) and (6) yields the model.

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<sup>6</sup>We assume that households base their energy demand on the energy cost of the previous year. We also control for potential endogeneity due to energy prices in the model using the lag of energy prices. The error correlation term between electricity prices and gas prices to effective carbon dioxide emissions is respectively 0.0413 and 0.0178 and no significant in both cases with a p-value equal to 0.133 and 0.468

## 4 Results and quality of estimates

### 4.1 Quality tests of instruments and quality of estimates

We propose three estimates: a simple first approach using OLS, and then two two-step estimates, one using a 2SLS methodology, and one using maximum likelihood, involving use of both the instruments. To bring some empirical proofs of the consistency of the instruments, we employ a three-step methodology. First, we conduct a significance test and a Wald test to ensure the quality of instruments in the endogenous estimate (see Table 4). The F statistic is above the often-used threshold of 10. Suppose that we are willing to accept at most a rejection rate of 10% of a nominal 5% Wald test. Here we can reject the null hypothesis that the instruments are weak, because the test statistic of 22.83 exceeds its critical value of 19.93. On the basis of this test, we do not have a weak-instrument problem. Having an elevator has a negative effect on theoretical energy efficiency. Clearly, elevators are more numerous in buildings of recent construction<sup>7</sup> and therefore denote better energy efficiency. In contrast, the greater the length of time since moving in, the higher the theoretical emissions. Buildings that consume more energy are not of recent construction as a result of energy efficiency regulations. The regulatory effect of new construction seems stronger than the hypothesis that housing that has been lived in a long time may have been renovated. It is reasonable to assume that a household who moved in a decade ago, moved into an older building as the newer buildings did not exist yet.

Second, we carry out tests for the instruments (identification and exogeneity) using the Durbin (1954[17]) and Wu (1974[46]) tests of endogeneity and the Wooldridge (1995[45]) robust score test (see Table 4). In all cases, if the test statistic is significant, then the variables being tested must be treated as endogenous. We perform tests to determine whether endogenous regressors in the model are in fact exogenous. After 2SLS estimation with an adjusted VCE, the Wooldridge (1995[45]) robust score test and a robust regression-based test are determined. The results are compared with a model without a robust VCE. We tabulate the Sargan (1958[41]) and Basman (1960[5])  $\chi^2$  tests noting that a statistically significant test statistic always indicates that the instruments seem to be good instrument.

Finally, we validate the correlation error terms. It is statistically significant which shows the relevance of considering potential endogeneity in the model. We were concerned that the errors in effective emissions per square meter and the choice of energy efficiency of the building (theoretical emissions) would be correlated. Table 5 in the next section shows that the errors are indeed negatively correlated (-0.6947) and it is significant. Unobserved heterogene-

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<sup>7</sup>The most recent French Law (November 2018) on housing, development and digital technology requires, among other things, the provision of an elevator for all buildings of three or more stories.

Table 4: Statistics after 2SLS regression

Statistics	statistics	p-value
Durbin (score) $\chi^2(1)$	39.8229	0.0000
Wu-Hausman F(1,1988)	40.2035	0.0000
Sargan (score) $\chi^2(3)$	0.781634	0.3766
Basman $\chi^2(3)$	0.773765	0.3791
Robust score $\chi^2(1)$	44.5898	0.0000
Robust regression F(1,1988)	49.061	0.0000
Score $\chi^2(1)$	0.9614	0.3268
F(2,1988)	22.8268	0.000

ity that describes effective CO<sub>2</sub> emissions is negatively correlated to unobserved heterogeneity explaining the choice of the dwelling's energy efficiency. Although this negative result may seem counter-intuitive, it is confirmed in the regressions on energy consumption (see Table 11 in the appendix). However there may be an explanation for that result. Households choose high-performance housing to enjoy energy savings in the knowledge they will over-consume (due to a preference for thermal comfort). In the first case, the choice of a high-performance dwelling could come from a preference for energy savings and in the second case, high actual emissions can be the result of a preference for thermal comfort. This result can explain a negative error correlation term.

We subsequently compare the estimated results using 2SLS, and the results obtained using a maximum likelihood. Using this last methodology to estimate the coefficients of the main equation, the endogenous regressor equations, and the variance and correlation parameters enables us to improve the quality of the estimates compared with the 2SLS procedure. When employing the linear prediction (fitted values) to estimate covariate effects, the maximum likelihood method allows prediction of the mean of the response conditional on the covariates and instruments in contrast to the 2SLS method. Using both methods, we predicted the conditional mean (3.14). But comparing both methods, we note that the conditional mean is a better predictor of CO<sub>2</sub> emissions than the linear prediction by comparing the mean squared errors (respectively 0.441. vs 1.042).

## 4.2 Results

Table 5: Results : Estimates of CO<sub>2</sub> emissions

VARIABLES	OLS		with endogeneity control - 2SLS		with endogeneity control - Maximum likelihood	
	First stage	Second stage	First stage	Second stage	First stage	Second stage
Socio-demographic characteristics						
Disposable income	-0.00213 (0.0380)	0.0948* (0.0572)	-0.0981*** (0.0360)	0.0985*** (0.0358)	0.0965* (0.0588)	
Age	0.00652*** (0.00141)	-0.00240 (0.00253)	0.00438*** (0.00160)	0.00408*** (0.00152)	-0.00255 (0.00272)	
Number of persons	0.103*** (0.0177)	0.133*** (0.0254)	-0.0371** (0.0169)	-0.0362** (0.0168)	0.133*** (0.0261)	
Male	0.0581 (0.0423)	0.0900 (0.0568)	-0.0363 (0.0387)	-0.0357 (0.0384)	0.0906 (0.0585)	
Prices						
Electricity price in 2011	0.383*** (0.142)	-0.943*** (0.322)	1.289*** (0.132)	1.289*** (0.131)	-0.966*** (0.362)	
Gas price in 2011	0.0124 (0.150)	-0.391* (0.212)	0.332** (0.145)	0.333** (0.145)	-0.398* (0.226)	
Interaction parameters between prices	0.0529 (0.0769)	-0.246** (0.116)	0.262*** (0.0739)	0.263*** (0.0735)	-0.251** (0.126)	
Climate and Location						
Unified Degree Days	7.34e-05*** (2.48e-05)	-1.71e-05 (3.92e-05)	7.60e-05*** (2.54e-05)	7.69e-05*** (2.54e-05)	-1.87e-05 (4.16e-05)	
Rural	0.322*** (0.0522)	0.145* (0.0789)	0.147*** (0.0465)	0.149*** (0.0463)	0.142* (0.0819)	
2,000 to 4,999 inhabitants	0.371*** (0.0688)	0.124 (0.113)	0.212*** (0.0696)	0.214*** (0.0692)	0.120 (0.116)	

Appliances					
Thermostat	-0.326*** (0.0717)	0.328*** (0.0653)	-0.636*** (0.128)	0.329*** (0.0651)	-0.641*** (0.136)
Portable air conditioner	-0.0121 (0.0783)	-0.181** (0.0862)	0.185 (0.118)	-0.183** (0.0858)	0.188 (0.121)
Vacancy and Behavior					
Vacancy period (days)	-0.000865 (0.000543)	-0.000521 (0.000324)	-0.000271 (0.000726)	-0.000527 (0.000320)	-0.000261 (0.000766)
Cold problem due to heating restriction	-0.0348 (0.0518)	0.268*** (0.0474)	-0.282*** (0.0843)	0.270*** (0.0471)	-0.287*** (0.0910)
Never turn down the heating (windows open)	0.0443 (0.0385)	0.0380 (0.0370)	-0.000123 (0.0523)	0.0379 (0.0368)	-0.000901 (0.0543)
Never turn down the heating during periods of inoccupancy	-0.0661 (0.0571)	-0.111** (0.0529)	0.0774 (0.0803)	-0.113** (0.0526)	0.0799 (0.0855)
Open windows during the heating season	0.0634 (0.0515)	-0.0918 (0.0567)	0.142* (0.0810)	-0.0926 (0.0565)	0.143* (0.0828)
Do not turn down the heating	0.0992** (0.0428)	-0.0500 (0.0400)	0.152*** (0.0582)	-0.0493 (0.0397)	0.153*** (0.0591)
Building efficiency					
Theoretical CO2/m2	0.299*** (0.0281)		1.291*** (0.193)		1.309*** (0.227)
Instruments					
Duration since move-in		0.00703*** (0.00158)		0.00759*** (0.00127)	
Elevator		-0.321*** (0.0541)		-0.283*** (0.0512)	
Error term correlation					
					-0.6947*** (0.0752)
Constant	2.153*** (0.517)	5.997*** (0.472)	-3.696*** (1.352)	6.001*** (0.470)	-3.799** (1.527)
Observations	2,009	2,009	2,009	2,009	2,009

Bootstrapped standard errors in brackets, 5000 replications.

Significance at the 10%, 5% and 1% levels are indicated respectively by \*, \*\* and \*\*\*.



We have showed the necessity of considering the endogeneity of the dwelling’s efficiency. Disregarding this endogeneity permits consideration of a direct causal impact of age on carbon emissions (Table 5, Column 1). With each additional year of life there is an increase of 0.0065 kg in effective CO<sub>2</sub> emissions per square meter g. However, such an approach ignores the selection bias and consequently hides a more complex reality. Demographics affect emissions through different channels that we disentangle by assuming a parameter of building energy where households first choose their housing and second adopt a consumption behavior while living there (Table 5, Columns 2 and 3).

We find that the age explains the choice of theoretical dwelling efficiency and not effective CO<sub>2</sub> emissions. Each additional year of life increases theoretical CO<sub>2</sub> emissions from 0.0041 to 0.0044 kg per square meter. Risch and Salmon (2017 [39]) found a positive effect of age on heating with gas or oil (leading to the greatest emissions) and a negative effect of age on heating with electricity (leading to the lowest emissions), which is consistent with our results. The age of the head of household increases the theoretical emissions per m<sup>2</sup>. Thus, our results differ from those of Brounen, *et al.* (2012 [10]) : energy use does not increase because the elderly prefer to consume more. These key results confirm assumptions obtained using descriptive statistics. The elderly are less mobile: the probability of moving to another dwelling decreases with age, which probably explains why older people live in less efficient housing. Our results show that the increased emissions related to older households are simply due to their dwellings, which are on average older and therefore less efficient.

Moreover, the effect of age on effective emissions is no longer significant in the main equation, once the housing energy-efficiency choice is made. Ignoring the endogeneity of the heating system therefore leads to the interpretation that age has a direct impact on effective CO<sub>2</sub> emissions. However, this is not the case. Age plays an endogenous role in the choice of housing, which explains the emissions. But once energy efficiency of housing is taken into account, age as such no longer explains the variability of emissions. These results differ from those of Belaid and Garcia (2016 [8]) who did not use the same methodology. Older people do not consume more energy (leading to greater emissions). We did not find greater behavioral inertia on the part of older people (Hines, *et al.*, 1987 [25]) nor a tendency to consume more energy for heating.

We show in the appendix (see Table 8) that considering theoretical emissions only is not sufficient to explain effective CO<sub>2</sub> emissions: we regress effective CO<sub>2</sub> emissions by theoretical emissions, without any other control variable. The  $R^2$  is quite low and equal to 0.13 (close to the 0.16 of Brounen *et al.*, 2012 [10]). This demonstrates that the considerable variability

in CO<sub>2</sub> emissions in the residential sector remains unexplained once controlling for building weatherization and location. Once again, controlling endogeneity is essential to avoid miscalculation of parameters and misunderstanding results. The impact of the theoretical CO<sub>2</sub> emissions parameter seems limited if we only consider the OLS estimate: each additional CO<sub>2</sub> kg increases effective emissions by 0.37 kg. This parameter becomes quite elastic after correcting for endogeneity, reaching 1.13 or 1.15 depending on methodology. The same results with other controls (0.30 vs 1.30) are shown in Table 5.

The parameter of household size is one of the most important factors influencing CO<sub>2</sub> emissions. According to the literature, economies of scale emerge with larger households. Our results indeed confirm that adding one inhabitant increases the dwelling's theoretical efficiency: CO<sub>2</sub> emissions decrease significantly from 0.36 to 0.37 kg per square meter. At first glance, it would appear that larger households are looking for more efficient housing (or with better environmental performance), confirming then the potential existence of economies of scale. However, after having chosen the theoretical efficiency level of their dwelling, consumption behaviors tend to show CO<sub>2</sub> emissions per square meter increasing with the number of household members. The final effect of household size therefore seems difficult to determine: increased theoretical efficiency within larger households is offset by effective consumption behaviors. Nevertheless, this result tends to support our findings: older households have fewer members, leading them to live in less efficient housing, although they consume more moderately.

Carbon dioxide emissions (or energy) is a normal good with an income elasticity between 0.095 and 0.097 (Bakaloglou and Charlier, 2019 [1]; Cayla, *et al.*, 2011 [13]; Labandeira, *et al.*, 2006 [28]). An environmental footprint tends to increase with income (Buchs and Schnepf, 2013 [11]; Longhi, 2015 [31]). It is also a typical good, commonly described in the literature, but with a higher price elasticity for electricity (the most expensive energy in France) than for gas (respectively between -0.94 and -0.97 for electricity and between -0.39 and -0.40 for gas). The higher elasticity for electricity can be also due to the fact that is energy is used in many more applications. Our results are consistent with the literature (Labandeira, *et al.*, 2017). Having a thermostat leads to lower effective emissions, which is in line with expectations. Having a portable air conditioner has a negative effect on the theoretical emissions of dwelling whereas it does not have an impact on effective emissions. Owning a portable conditioner reduces the likelihood of living in inefficient housing. We will prefer to choose an efficient dwelling because we know that we are going to use a little more electricity to run it.

Opening windows explains greater emissions as does not turning the heating down during

the heating season. In general, the parameter describing building energy efficiency especially after controlling for endogeneity is quite strong. Once again, ignoring this methodological problem can lead to an underestimation of the influence of theoretical efficiency, although this is not sufficient to explain all variability.

After having examined the impact of age on theoretical and actual emissions, we examined whether different CO<sub>2</sub> emission profiles emerge among individuals under 60 and individuals over 60 (see Table 6). We believe that older households live in housing chosen in earlier decades, and that given their low mobility, their past choices particularly affect their current environmental footprint, which is less true for younger and more mobile households. Results presented in Table 6 appear to confirm our first assumption.

Income significantly affects both choice and effective CO<sub>2</sub> emissions before the age of 60 but not after. There is a life-cycle effect. Income and number of inhabitants suggest a social environment which differentiates people under 60 from people over 60. In addition, price sensitivity is quite inelastic for electricity among the elderly and not significant for gas, which differs significantly from the youngest age category. Energy can be considered to be a good that prevents problems such as poor health, and the elderly cannot adjust their consumption after a change in energy prices (Warriner, 1981 [44]). They may therefore be more vulnerable (as long as their income does not change) to problems of fuel poverty (Legendre and Ricci, 2015 [30]). Two points can be made. First, the inelasticity of emissions to price shows that in times of increasing energy prices, older people will have to give up other consumption to maintain a temperature compatible with the desired or necessary level of comfort. However, we can also question this inelasticity and argue that retired people, whose incomes have fallen, have already adopted a restricted consumption behavior, leaving no room for further adjustment of the quantity of energy consumed. The phenomenon of fuel poverty already highlighted in the literature can be exacerbated by the fact that older households have less air conditioning than other types of households, and live in poorly insulated dwellings, making them more vulnerable to overheating during the increasingly frequent summer heat waves.

After the age of 60, the effect of gender is marked. If the head of the household is male, the household consumes more energy, which is consistent with a body of literature showing that women care more about the environment. Most studies report a positive relation between being male and CO<sub>2</sub> emissions: the proportion of high consumers of energy is much greater among males than among females (Barla, *et al.*, 2011 [4], Bel and Rosell, 2017 [6]). The literature also reports that women prefer a higher ambient temperature than men (Brounen *et al.*, 2012 [10]). Finally, it is again shown that there is no marked difference in behavior between

Table 6: Results by age

VARIABLES	Under 60		Over 60	
	First stage	Second stage	First stage	Second stage
<b>Socio-demographic characteristics</b>				
Disposable income	-0.101** (0.0449)	0.143* (0.0868)	-0.0884 (0.0611)	0.0445 (0.0783)
Number of persons	-0.0481*** (0.0184)	0.161*** (0.0399)	0.00810 (0.0508)	0.0745 (0.0613)
Male	0.0119 (0.0475)	0.0204 (0.0786)	-0.125* (0.0704)	0.180** (0.0884)
<b>Prices</b>				
Electricity price in 2011	1.243*** (0.181)	-1.315** (0.652)	1.340*** (0.184)	-0.661* (0.357)
Gas price in 2011	0.300 (0.193)	-0.461 (0.339)	0.349 (0.213)	-0.388 (0.288)
Interaction parameters between prices	0.258*** (0.0984)	-0.339* (0.201)	0.253** (0.108)	-0.187 (0.152)
<b>Climate and Location</b>				
Unified Degree Days	9.95e-05*** (3.04e-05)	-4.41e-05 (7.21e-05)	2.89e-05 (4.28e-05)	1.00e-05 (4.94e-05)
Rural	0.0982* (0.0594)	0.125 (0.115)	0.213*** (0.0737)	0.189* (0.105)
2,000 to 4,999 inhabitants	0.218*** (0.0828)	-0.0164 (0.177)	0.189 (0.124)	0.296* (0.162)
<b>Appliances</b>				
Thermostat	0.368*** (0.0800)	-0.696*** (0.236)	0.264** (0.110)	-0.652*** (0.166)
Portable air conditioner	-0.317*** (0.103)	0.396* (0.226)	-0.0377 (0.140)	0.0473 (0.138)
<b>Vacancy and Behavior</b>				
Vacancy period (days)	0.00206 (0.00199)	-0.00538 (0.00359)	-0.000554 (0.000388)	-0.000407 (0.000250)
Cold problems due to heating restriction	0.234*** (0.0572)	-0.299** (0.137)	0.313*** (0.0842)	-0.275** (0.118)
Never turn down the heating (windows open)	-0.00842 (0.0467)	0.0686 (0.0770)	0.0905 (0.0598)	-0.0660 (0.0744)
Never turn down the heating during periods of inoccupancy	-0.215*** (0.0681)	0.258 (0.162)	0.0139 (0.0798)	-0.0683 (0.107)
Open windows during the heating season	-0.103 (0.0634)	0.155 (0.124)	-0.125 (0.111)	0.208* (0.117)
Do not turn down the heating	-0.118** (0.0520)	0.235** (0.106)	0.0355 (0.0617)	0.108 (0.0782)
<b>Building efficiency</b>				
Theoretical CO2/m2		1.581*** (0.458)		1.099*** (0.171)
<b>Instruments</b>				
Duration since move-in	0.00701*** (0.00202)		0.00864*** (0.00160)	
Elevator	-0.170*** (0.0637)		-0.433*** (0.0740)	
Error term correlation		-0.781*** (0.105)		-0.581*** (0.0912)
Constant	6.073*** (0.611)	-5.830** (2.973)	6.379*** (0.734)	-2.204 (1.501)
Observations	1,205	1,205	804	804

Bootstrapped standard errors in brackets, 5000 replications.

Significance at the 10%, 5% and 1% levels are indicated respectively by \*, \*\* and \*\*\*.

those over 60 and those under-60: those under 60 never turn off the heat during the heating season. More people over 60 open windows during the heating season but this result is slightly significant at only 10% and is consistent with health recommendations on airing your home for 15 minutes a day.

Our results are robust to several specifications, with or without control variables, and with progressive addition of the variables (See Tables 9 and 10 in the appendix).

## 5 Conclusion and discussion

An aging population calls into question the sustainability of a society. Indeed, lifestyles and consumption patterns are closely linked to the age of individuals. Aging is likely to lead to profound changes in energy consumption habits. Peoples are living longer, leading to changes in household composition and housing choices. A good understanding of the determinants of energy consumption has become essential both to reduce dependence on certain types of energy and to preserve the environment, which is threatened by global warming. We aim to highlight the impact of age in particular on CO<sub>2</sub> emissions in recent times, in order to better understand the impact that aging could have and thus contribute to the formulation of future energy policies.

Two categories of variables have an impact on energy consumption: on the one hand the technical and non-human attributes of the dwelling, and on the other energy consumption behavior. Much progress has been made in the energy economics literature through the acquisition of microeconomic data to study behavior and housing, but also through methodological progresses to take into account the links between human and non-human factors affecting energy consumption. In the present paper we integrate the literature on the determinants of energy consumption with the latest methodological advances allowing us to affirm that CO<sub>2</sub> emissions respond to a strong logic of self-selection by households according to age. We therefore show that age has a significant impact on the theoretical emissions of housing. Older households have lived in their dwelling for a longer period of time, and older buildings are less energy efficient on average. The higher emissions related to older households are therefore indirectly due to the past choice they made when they chose their dwelling and its technical characteristics. But once this self-selection through choice is controlled, age no longer has an impact on the actual emissions related to the dwelling. Our results therefore contradict some existing studies which conclude that there is an exaggerated preference for greater energy consumption among older people. We have therefore disentangled two potential channels of impact of age on emissions, the housing efficiency channel and the behavioral channel, but

have shown that only the former has a significant impact.

The literature submits that the elderly have less economical consumption patterns than younger generations. Such conclusions suggest that the elderly should be the target of policies encouraging more moderate energy consumption. Our results challenge this notion. They shed new light on economic policy: policies that encourage more moderate consumption, especially for elderly people, are not needed to restrict CO<sub>2</sub> emissions (which does not mean they are never useful). We focused on the intensive margin of CO<sub>2</sub> emissions, showing that older people have lived in their homes for a long time, which are less likely to have been renovated. As a consequence, this more CO<sub>2</sub> emissions are generated. The question of the extensive margin of emissions arises: while an aging population does not mean an absolute increase in the amount of poor quality housing, it nevertheless leads to a certain inertia in the renovation of the existing housing stock. This therefore confirms the need to be vigilant about energy renovations in countries where the population is rapidly aging. A sustained policy of housing renovation, particularly for older people, seems necessary to limit the increased emissions linked to demographic aging which in turn leads to aging of the existing building stock. This type of policy could also be part of a set of social measures targeting the elderly, whose consumption is inelastic to price. Thus, better-insulated housing will make it possible to limit the impact of energy price rises on the well-being of the elderly.

Demographic aging presents many challenges for Western societies, which were the first to be confronted by it. But beyond changes in energy consumption patterns, there will be marked changes in housing-related choices and behavior in the coming decades, particularly due to the increasing number of elderly with disabilities or other health problems. Policies related to housing improvements will certainly have to include improved energy efficiency to limit emissions and increase the thermal comfort of the aging population, but they will also have to enable people to maintain their independence and remain in their own homes as long as possible. Policies related to the loss of autonomy of older people place great emphasis on maintaining the independence of the elderly. Placement in specialized institutions should take place only when all alternatives have been exhausted. This approach is also in line with the wishes of the elderly, who often find it very traumatic to leave their home.

## References

- [1] S. Bakaloglou and D. Charlier. Energy consumption in the French residential sector: How much do individual preferences matter? *Energy Journal*, 40, 2019.
- [2] K. Baker and R.M. Rylatt. Improving the prediction of UK domestic energy-demand using annual consumption-data. *Applied Energy*, 85:475–482, 2008.
- [3] R. Bardazzi and M.G. Pazienza. Switch off the light, please! energy use, aging population and consumption habits. *Energy Economics*, 65(161-171), 2017.
- [4] P. Barla, L.F. Miranda-Moreno, and M. Lee-Gosselin. Urban travel CO2 emissions and land use: A case study for Quebec City. *Transportation Research Part D: Transport and Environment*, 16:423–428, 2011.
- [5] R.L. Basmann. On finite sample distributions of generalized classical linear identifiability test statistics. *ournal of the American Statistical Association*, 55:650–659, 1960.
- [6] G. Bel and J. Rosell. The impact of socioeconomic characteristics on CO2 emissions associated with urban mobility: Inequality across individuals. *Energy Economics*, 64:251–261, 2017.
- [7] F. Belaid. Untangling the complexity of the direct and indirect determinants of the residential energy consumption in France: Quantitative analysis using a structural equation modeling approach. *Energy Policy*, 110:246–256, 2017.
- [8] F. Belaid and T. Garcia. Understanding the spectrum of residential energy-saving behaviours: French evidence using disaggregated data. *Energy Economics*, 57:204–214, 2016.
- [9] W. Biesiot and K.J. Noorman. Energy requirements of household consumption: a case study of The Netherlands. *Ecological Economics*, 28:367–83, 1999.
- [10] D. Brounen, N. Kok, and J.M. Quigley. Residential energy use and conservation: Economics and demographics. *European Economic Review*, 56:931–945, 2012.
- [11] M. Buchs and S.V. Schnepf. Who emits most? associations between socio-economic factors and UK households’ home energy, transport, indirect and total CO2 emissions. *Ecological Economics*, 90:114–123, 2013.
- [12] A. Carlsson-Kanyama, A.-L. Linden, and B. Eriksson. Residential energy behavior: does generation matter? *International Journal of Consumer Studies*, 29:239–253, 2005.
- [13] J.-M. Cayla, N. Maizi, and C. Marchand. The role of income in energy consumption behaviour: Evidence from French households data. *Energy Policy*, 39:7874–7883, 2011.

- [14] L. Chancel. Are younger generations higher carbon emitters than their elders?: Inequalities, generations and co2 emissions in France and in the USA. *Ecological Economics*, 100:195–207, 2014.
- [15] D. Charlier and S. Kahouli. From residential energy demand to fuel poverty: Income-induced non-linearities in the reactions of households to energy price fluctuations. *Energy Journal*, 40:101–137, 2019.
- [16] Avinash. K. Dixit and Robert. S. Pindyck. *Investment Under Uncertainty*. Princeton University Press, 1994.
- [17] J. Durbin. Errors in variables. *Review of the International Statistical Institute*, 22(1/3):23–32, 1954.
- [18] J.A. Durbin and D.L. McFadden. An econometric analysis of residential electric appliance holdings and consumption. *Econometrica*, 52:345–362, 1984.
- [19] H. Estiri. The indirect role of households in shaping us residential energy demand patterns. *Energy Policy*, 86:585–594, 2015.
- [20] S. Frondel, F.M. Flores, and C. Vance. Heterogeneous rebound effects: Comparing estimates from discrete-continuous models. USAEE Working Paper 16. RWI - Leibniz-Institut für Wirtschaftsforschung, Ruhr-University Bochum, TU Dortmund University, University of Duisburg-Essen, Ruhr Economic Papers, 2016.
- [21] B. Gatersleben, L. Steg, and C. Vlek. Measurement and determinants of environmentally significant consumer behavior. *Environment and Behavior*, 34:335–362, 2002.
- [22] N. Hamza and 2011 Gilroy, R. The challenge to UK energy policy: An ageing population perspective on energy saving measures and consumption. *Energy Policy*, 39:782–789, 2011.
- [23] and Lyons S. Harold, J. and J. Cullinan. The determinants of residential gas demand in ireland. *Energy Economics*, 51:475–483, 2015.
- [24] Claude Henry. Investment decisions under uncertainty: The "irreversibility effect". *American Economic Review*, 64(5):1006–1012, 1974.
- [25] J.M. Hines, H.R. Hungerford, and A.N. Tomera. Analysis and synthesis of research on responsible environmental behavior: A meta-analysis. *The Journal of Environmental Education*, 18:1–8, 1987.
- [26] B.S. Koirala, A.K. Bohara, and H. Li. Effects of energy-efficiency building codes in the energy savings and emissions of carbon dioxide. *Environmental Economics and Policy Studies*, 15:271–290, 2013.



- [27] Labeaga J.M. López-Otero X. 2017. . 102 549-568 Labandeira, X. A meta-analysis on the price elasticity of energy demand. *Energy Policy*, 2017.
- [28] X. Labandeira, J.M. Labeaga, and M. Rodriguez. A residential energy demand system for spain. *The Energy journal*, 27:87–111, 2006.
- [29] D.A. Lashof and D.R. Ahuja. Relative contributions of greenhouse gas emissions to global warming. *Nature*, 344:529–531, 1990.
- [30] B. Legendre and O. Ricci. Measuring fuel poverty in France: Which households are the most fuel vulnerable? *Energy Economics*, 49:620–628, 2015.
- [31] S. Longhi. Residential energy expenditures and the relevance of changes in household circumstances. *Energy Economics*, 49:440–450, 2015.
- [32] H. Meier and K. Rehdanz. Determinants of residential space heating expenditures in great britain. *Energy Economics*, 32:949–959, 2010.
- [33] Mohammad K. Najjar, Karoline. Figueiredo, Ahmed W. A. Hammad, Vivian. W. Y. Tam, Ana Catarina Jorge Evangelista, and Assed.and Haddad. A framework to estimate heat energy loss in building operation. *Journal of Cleaner Production*, 235:789–800, 2019.
- [34] P.K. Narayan and R. Smyth. The residential demand for electricity in Australia: an application of the bounds testing approach to cointegration. *Energy Policy*, 33:467–474, 2005.
- [35] R. Nesbakken. Price sensitivity of residential energy consumption in norway. *Energy Economics*, 21:493–515, 1999.
- [36] R. Nesbakken. Energy consumption for space heating: A discrete-continuous approach. *Scandinavian Journal of Economics*, 103:165–184, 2001.
- [37] R.S. Pindyck. Irreversibility, uncertainty, and investment. *Journal of Economic Literature*, 29(3):1110–1148, 1991.
- [38] K. Rehdanz. Determinants of residential space heating expenditures in germany. *Energy Economics*, 29:167–182, 2007.
- [39] A. Risch and C. Salmon. What matters in residential energy consumption: evidence from France. *International Journal of Global Energy Issues*, 40:79–115, 2017.
- [40] M. Santamouris, K. Kapsis, D. Korres, I. Livada, C. Pavlou, and M.N. Assimakopoulos. On the relation between the energy and social characteristics of the residential sector. *Energy and Buildings*, 39:893–905, 2007.

- [41] J. D. Sargan. The estimation of economic relationships using instrumental variables. *Econometrica*, 26:393–415, 1958.
- [42] C. Schroder, K. Rehdanz, D. Narita, and T. Okubo. The decline in average family size and its implications for the average benefits of within-household sharing. *Oxford Economic Papers*, 65, 2015.
- [43] K. Vaage. Heating technology and energy use: a discrete/continuous choice approach to norwegian household energy demand. *Energy Economics*, 22:649–666, 2000.
- [44] G.K. Warriner. Electricity consumption by the elderly: Policy implications. *Journal of Consumer Research*, 8(258-264), 1981.
- [45] J.M. Wooldridge. *Advances in Econometrics and Quantitative Economics: Essays in Honor of Professor C. R. Rao*, chapter Score diagnostics for linear models estimated by two stage least squares, pages 66–87. Blackwell, Oxford, 1995.
- [46] D.M. Wu. Alternative tests of independence between stochastic regressors and disturbances: Finite sample results. *Econometrica*, 42:529–546, 1974.

## 6 Appendix

Figure 5: Energy performance certificate - Energy performance

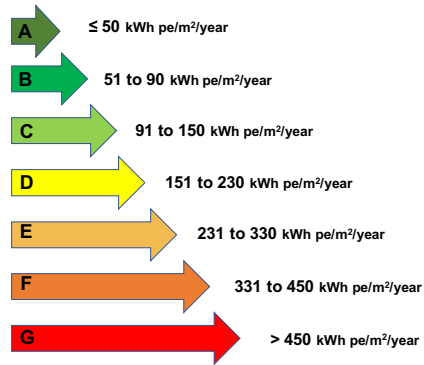


Figure 6: Energy performance certificate - Climate performance

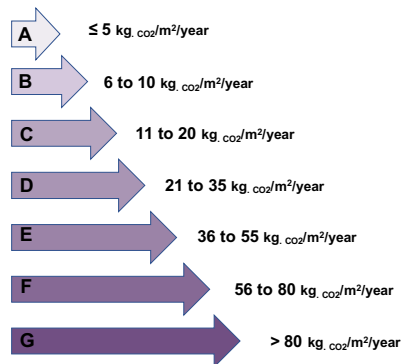


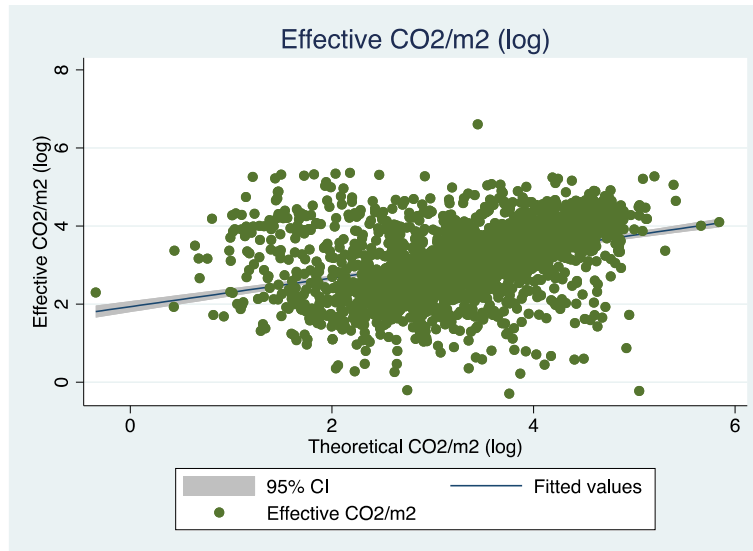
Table 7: Electricity and Gas Tarriffs

	2011	2012
<b>ELECTRICITY TARIFF</b>		
Electricity. blue rate. base option in euros (tax included)		
Annual subscription cost 3 kVA	64.94606	67.40325
Annual subscription cost 6 kVA	77.45169	80.36592
Annual subscription cost 9 kVA	90.3377	93.76717
Annual subscription cost 12 kVA	142.84527	148.13392
Annual subscription cost 15 kVA	164.85725	171.04758
Annual subscription cost 18 kVA	219.2238	227.44092
Price for 100 kWh (power 3 kVA)	17.02237	17.7994
Price for 100 kWh (power 6 kVA)	16.23193	16.9816
Electricity. blue rate. peak hours rate in euros (tax included)		
Annual subscription cost 6 kVA	93.13223	96.59658
Annual subscription cost 9 kVA	111.76704	115.91475
Annual subscription cost 12 kVA	189.49559	196.56458
Annual subscription cost 15 kVA	223.04773	231.32342
Annual subscription cost 18 kVA	254.38013	263.81675
Annual subscription cost 24 kVA	529.87303	549.78758
Annual subscription cost 30 kVA	652.50116	677.02358
Annual subscription cost 36 kVA	754.42164	782.73067
100 kWh peak-hours	12.91385	13.54292
100 kWh off-peak	8.76965	9.23933
Price for 100 kWh (power 6 kVA)	14.03546	14.70435
Price for 100 kWh (power 9 kVA)	13.02266	13.65389
Price for 100 kWh (power 12 kVA)	12.77758	13.39973
Electricity. blue rate. tempo option in euros (tax included)		
Annual subscription cost 9 kVA	109.04157	113.022
Annual subscription cost 12 kVA	203.35865	210.90942
Annual subscription cost 30 kVA	456.64613	473.54025
Annual subscription cost 36 kVA	566.42158	587.43975
100 kWh blue days and off-peak	6.8142	7.2111
100 kWh blue days and peak-hours	8.20155	8.65528
100 kWh white days and off-peak	9.8401	10.35061
100 kWh white days and peak-hour	11.7537	12.33594
100 kWh red days and off-peak	18.5589	19.40033
100 kWh red days and peak-hour	49.16455	51.17409
Electricity. market rate. in euros (tax included)		
All rates	13.41974	13.82434
DA rate	24.45679	25.13133
DB rate	15.8404	16.3847
DC rate	14.02566	14.45913
DD rate	12.84391	13.2134
DE rate	12.54369	12.91665
<b>GAS RATE</b>		
Natural Gas. price in euros (tax included)		
Annual subscription cost - base rate	43.8933	46.92645
Annual subscription cost - B0 rate	58.0092	61.97075
Annual subscription cost - B1 rate	185.18415	195.4546
Annual subscription cost - B2I rate	185.18415	195.4546
100 kWh PCS - base rate	9.3988	9.96987
100 kWh - B0 rate	8.0742	8.51871
100 kWh- B1 rate	5.58353	5.86163
100 kWh - B2I rate	5.58353	5.86163
Price for 100 kWh B0 rate	11.74238	12.42551
Price for 100 kWh B1 rate	7.08853	7.44654
Price for 100 kWh B2I rate	6.79365	7.13536

Table 8: Effective CO<sub>2</sub> emissions explained by theoretical CO<sub>2</sub> emissions

VARIABLES	OLS	2SLS		ML	
		2nd stage	1st stage	2nd stage	1st stage
Theoretical CO <sub>2</sub> /m <sup>2</sup>	0.367*** (0.0249)		1.126*** (0.132)		1.155*** (0.133)
Duration since move-in		0.0108*** (0.00135)		0.00987*** (0.00128)	
Elevator		-0.327*** (0.0715)		-0.412*** (0.0628)	
Constant	1.935*** (0.0895)	3.123*** (0.0327)	-0.573 (0.431)	3.145*** (0.0306)	-0.668 (0.436)
Error terms correlation					-0.655*** (0.0644)
Observations	2009	2009	2009	2009	2009
R-squared	0.131		0.042		
Wald chi2(1) - pvalue		73.12 p=0.0000		74.98 p= 0.0000	

Figure 7: ML regression of effective CO<sub>2</sub> emissions on theoretical CO<sub>2</sub> emissions



Source : Authors' calculus

Table 9: Robustness checks 1 (effect of age on the second stage)

VARIABLES	Benchmark		Sub-regression 1		Sub-regression 2		Sub-regression 3		Sub-regression 4	
	First stage	Second stage	First stage	Second stage	First stage	Second stage	First stage	Second stage	First stage	Second stage
Age	0.00438*** (0.00160)	-0.00240 (0.00253)	0.00520*** (0.00166)	-0.00441 (0.00292)	0.00371** (0.00144)	-0.00248 (0.00246)	0.00384*** (0.00147)	-0.00262 (0.00268)	0.00401*** (0.00149)	-0.00252 (0.00258)
Socio-demographic characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Prices	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climate and location	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes
Appliances	Yes	Yes	No	No	No	No	No	No	Yes	Yes
Vacancy and behavior	Yes	Yes	No	No	No	No	No	No	No	No
Theoretical emissions	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Instruments	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Error terms correlation		-0.6947*** (0.0752)		-0.771*** (0.0615)		-0.734*** (0.0587)		-0.742*** (0.0704)		-0.711*** (0.0720)
Observations	2009	2009	2009	2009	2009	2009	2009	2009	2009	2009

Bootstrapped standard errors in brackets, 5000 replications. Significance at the 10%, 5% and 1% levels are indicated respectively by \*, \*\* and \*\*\*.

Table 10: Robustness checks 2

VARIABLES	Sub-regression 1		Sub-regression 2		Sub-regression 3		Sub-regression 4		Sub-regression 5		Sub-regression 6	
	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage
Socio-demographic characteristics												
Age	0.00629*** (0.00151)	-0.0116*** (0.00306)			0.00520*** (0.00166)	-0.00441 (0.00292)						
Disposable income			-0.121*** (0.0405)	0.0778 (0.0561)	-0.130*** (0.0406)	0.106 (0.0649)						
Number of persons			-0.0215 (0.0175)	0.134*** (0.0233)	0.00299 (0.0188)	0.115*** (0.0276)						
Male			-0.108** (0.0448)	0.173*** (0.0616)	-0.113** (0.0446)	0.194*** (0.0705)						
Prices												
Electricity price in 2011					1.345*** (0.139)	-0.876*** (0.260)						
Gas price in 2011					0.385*** (0.148)	-0.322 (0.202)						
Interaction parameters between prices												
					0.285*** (0.0751)	-0.216** (0.107)						
Climate and Location												
Unified Degree Days									0.000103*** (2.94e-05)	-9.23e-06 (3.30e-05)		
Rural									-0.200*** (0.0488)	0.337*** (0.0647)		
2,000 to 4,999 inhabitants									-0.0327 (0.0731)	0.256*** (0.0873)		
Appliances												
Thermostat									0.505*** (0.0700)	-0.603*** (0.117)		
Portable air conditioner									-0.294*** (0.100)	0.151 (0.102)		

Vacancy and behavior										
Vacancy period (days)									-2.93e-05	-0.000854***
									(0.000434)	(0.000308)
Cold problem due to heating restriction										
									0.358***	-0.277***
									(0.0511)	(0.0704)
Never turn down the heating (windows open)										
									0.0243	0.0189
									(0.0417)	(0.0458)
Never turn down heating during periods of inoccupancy										
									-0.177***	-0.0101
									(0.0597)	(0.0740)
Open windows during the heating season										
									-0.128**	0.143**
									(0.0618)	(0.0689)
Do not turn down the heating										
									0.0507	0.104**
									(0.0447)	(0.0507)
Building Efficiency										
Theoretical CO2/m2	1.641***		1.328***		1.489***		1.170***		1.028***	1.012***
	(0.236)		(0.151)		(0.217)		(0.131)		(0.120)	(0.117)
Instruments										
Duration since move-in	0.00699***		0.00992***		0.00757***		0.00951***		0.0106***	0.0115***
	(0.00122)		(0.00119)		(0.00125)		(0.00115)		(0.00129)	(0.00134)
Elevator	-0.330***		-0.353***		-0.323***		-0.439***		-0.389***	-0.378***
	(0.0656)		(0.0646)		(0.0690)		(0.0456)		(0.0679)	(0.0613)
Error terms correlation	-0.808***		-0.722***		-0.771***		-0.647***		-0.589***	-0.564***
	(0.0526)		(0.0563)		(0.0615)		(0.0583)		(0.0709)	(0.0713)
Observations	2009	2009	2009	2009	2009	2009	2009	2009	2009	2009

Bootstrapped standard errors in brackets, 5000 replications.

Significance at the 10%, 5% and 1% levels are indicated respectively by \*, \*\* and \*\*\*.



Table 11: Robustness checks: energy consumption for fossil fuels

VARIABLES	First stage	Second Stage
<b>Socio-demographic characteristics</b>		
Disposable income (log)	-0.0805*** (0.0292)	0.132** (0.0649)
Age	0.00263** (0.00130)	0.000466 (0.00258)
Number of persons	-0.0401*** (0.0135)	0.00271 (0.0333)
Male	0.00697 (0.0307)	-0.0497 (0.0546)
<b>Prices</b>		
Electricity price in 2011 (log)	-0.152 (0.0983)	0.581*** (0.196)
Gas price in 2011 (log)	0.287*** (0.0945)	-0.932*** (0.295)
Interaction parameters between prices	0.136*** (0.0481)	-0.492*** (0.152)
<b>Climate and location</b>		
Unified Degree Days	3.98e-05* (2.24e-05)	-2.74e-05 (3.20e-05)
Rural	0.0263 (0.0382)	-0.0478 (0.0759)
2,000 to 4,999 inhabitants	0.0978** (0.0488)	-0.0112 (0.0904)
<b>Appliances</b>		
Thermostat	-0.148** (0.0597)	0.351*** (0.124)
Portable air conditioner	-0.120 (0.0762)	0.126 (0.119)
<b>Vacancy and behavior</b>		
Vacancy period (days)	-0.000379** (0.000174)	-0.000361 (0.000511)
Cold problem due to heating restriction	0.199*** (0.0365)	-0.0173 (0.0793)
Never turn down the heating (windows open)	0.0187 (0.0288)	0.0177 (0.0542)
Never turn down the heating during periods of inoccupancy	0.0415 (0.0435)	-0.123 (0.0852)
Open windows during the heating season	-0.0198 (0.0413)	0.0546 (0.0762)
Do not turn down the heating	-0.0570* (0.0301)	0.147** (0.0584)
<b>Building efficiency</b>		
Theoretical energy consumption/m2		0.973*** (0.331)
<b>Instruments</b>		
Elevator	-0.309*** (0.0616)	
Duration since move-in	0.00382*** (0.00110)	
Error term correlation	-0.344** (0.156)	

Bootstrapped standard errors in brackets, 5000 replications.

Significance at the 10%, 5% and 1% levels are indicated respectively by \*, \*\* and \*\*\*.