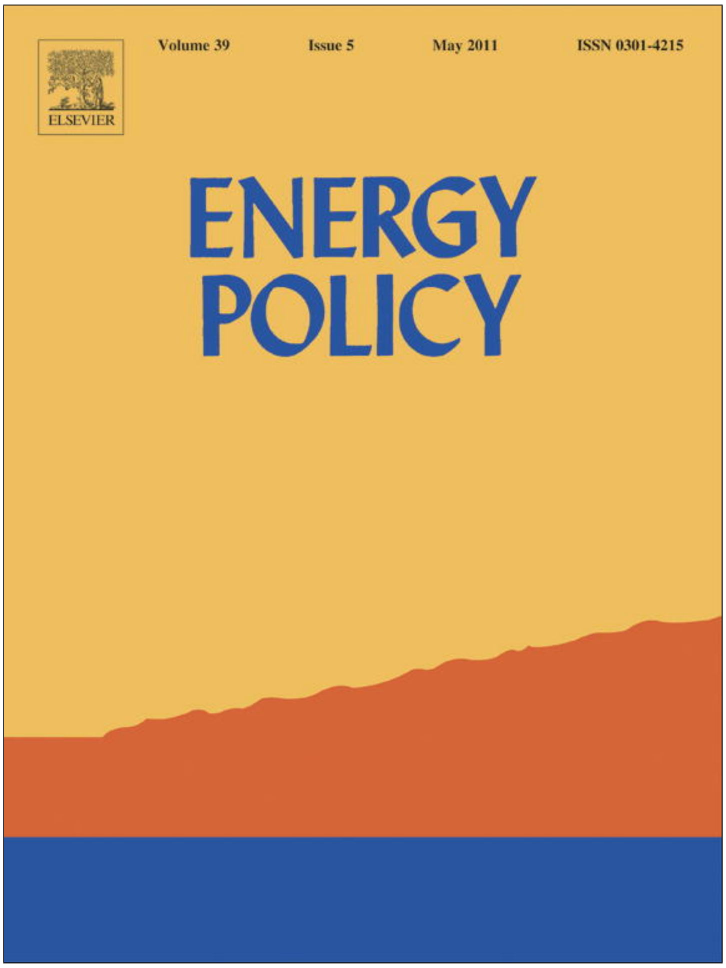
Volume 39
Issue 5
May 2011
ISSN 0301-4215
ELSEVIER
ENERGY
POLICY

Energy Policy 39 (2011) 2772–2779

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Residential electricity consumption in Portugal: Findings from top-down and bottom-up models

Daniel Wiesmann[a,*], Inês Lima Azevedo[b], Paulo Ferrão[a], John E. Fernández[c]

[a] Instituto Superior Técnico, Technical University of Lisbon, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal
[b] Department of Engineering and Public Policy, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA
[c] Department of Architecture, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ARTICLE INFO

Article history:
Received 12 July 2010
Accepted 15 February 2011

Keywords:
Residential electricity consumption
Econometrics
Portugal

ABSTRACT

An econometric study of the Portuguese residential electricity consumption is presented, with a focus on the influence of dwelling characteristics on consumption. The relationship between the dwelling and household characteristics on per capita residential electricity consumption is estimated at two different scales, involving two distinct databases: the first includes data at the municipality level for 2001, the second is the most recent Portuguese consumer expenditure survey that was collected in 2005 and 2006. The results of the analysis at both scales are consistent and indicate that household and dwelling characteristics have a significant influence on residential electricity consumption. Our results show that in Portugal the direct effect of income on electricity consumption is low and becomes smaller when more relevant control variables are included in the analysis. Future demand of electricity in Portugal will be significantly influenced by trends in socioeconomic factors as well as changes in the building stock. These trends should be taken in consideration in the formulation of policy measures to reduce electricity consumption.

1. Introduction

Obtaining a better understanding of the drivers of energy consumption has become an increasingly pressing issue over the last decades. It is an important issue for a number of reasons, but the most prominent ones are security of energy supply, climate change and affordability of energy. All of these concerns are directly linked to the way our societies consume energy. The strong dependence on fossil fuels has been recognized as a security threat in countries that are major importers of energy (Umbach, 2010; Bielecki, 2002) and affordability is an issue for transition economies (Fankhauser and Tepic, 2007). Climate change is largely driven by greenhouse gas (GHG) emissions that originate from the combustion of fossil fuels (IPCC, 2007). As a reaction to these facts, many countries committed to reduce GHG emissions under the Kyoto protocol (UNFCCC, 2010). Also, the promotion of renewable energy forms and diversification in energy sources is on the agenda of many of these countries.

Portugal is no exception in this regard. It is currently not meeting its GHG emission reduction targets that have been negotiated with the European Union (Eurostat, 2009b) and it imports 83% of its energy needs (Eurostat, 2009a). This has motivated the country to diversify its energy sources and brought energy policy to the forefront of the country's concerns. Portugal has significantly shifted its electricity production system by introducing natural gas power plants, new hydroelectric power plants and wind energy. Electricity production from natural gas has increased from zero to 12.3 TWh between 1996 and 2006 and has become a significant part of the total yearly electricity consumption of 46.9 TWh. The total installed capacity for production from all types of renewable energy sources has doubled from 1995 to 2009 and has reached 9.2 GW, by March 2010. Although the production capacity has grown for all types of renewable energy, the increase in this period has largely been driven by the introduction of 3.6 GW of capacity for the production of electricity from wind energy (DGEG, 2010).

Despite this significant increase of installed capacity, the share of renewable energy sources for electricity production has not yet increased. The five year average of the production of electricity from renewable energy sources in the period from 1994 to 1998 was 35%, whereas the five year average from 2004 to 2008 was 26% (DGEG, 2010). The reasons for this decrease are twofold. On the one hand the average production from renewable energy sources is almost the same for both periods. The higher capacity for production from renewable energy sources in the later period has not resulted in higher production due to the weather conditions. On the other hand the total electricity demand has constantly increased. The combination of both of these facts resulted in a relative decrease of the share of renewables.

* Corresponding author. Tel.: +1 93 838 73 66.
E-mail address: daniel.wiesmann@ist.utl.pt (D. Wiesmann).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.02.047

Compared with the European Union, Portugal has still a relatively low per capita consumption of energy (Eurostat, 2009a). With gross inland energy consumption per capita of 2.45 toe, the average Portuguese citizen consumes 30% less energy than the average citizen of the European Union. This difference goes down to 20% when only electricity consumption is considered. Similarly, the per capita GHG emissions are low by European standards, the emissions of CO_2 equivalent per capita are 7.7 tCO_2e in Portugal versus 10.2 tCO_2e in the European Union. The mix of primary energy consumption in the Portuguese residential sector by energy source in 2009 was as follows: liquefied propane gas 16%, natural gas 8%, other oil derived fuels 1%, electricity 38%, solar thermal 1% and biomass 36% (DGEG, 2011).

The council of ministers of Portugal has recently formulated an ambitious national energy strategy for 2020 (Presidência do Conselho de Ministros, 2010). The goals of this strategy include the reduction of energy dependence to 74% and to increase the share of renewable energy sources in final energy consumption to 31%. The goal for electricity generation is to reach 60% from renewable energy sources by 2020. The strategy also proposes to create economic clusters around the production of renewable energy and energy efficiency.

Policy measures targeted to reach these ambitious goals have to be well informed and, therefore, a good understanding of the drivers of electricity consumption is important. In this paper we study the residential electricity consumption in Portugal using multivariate regression analysis. The residential sector is responsible for about 17% of the country's total final energy consumption and for 21% of the total electricity consumption. We test variables describing household characteristics as well as the corresponding dwelling characteristics. We do so both at an aggregated level (top-down) and at the individual household level (bottom-up). This allows a direct comparison of results from different scales of analysis and increases the reliability of the estimates. We test a number of proxies that can be used to describe the housing stock at the aggregated level and that could possibly be integrated in future top-down studies.

Portugal provides a relevant case study as it represents a transitional economy, as discussed by Niza and Ferrão (2006). Its development pattern in the last decades show a linear correlation between natural resources consumption and GDP. This is a pattern that is being followed by the major emerging economies in the world, therefore analyzing its electricity demand structure can provide relevant insights for the global effort of sustainable development.

The rest of this paper is organized as follows: in Section 2 we provide an overview of the most recent literature that is relevant for this study. A description of the regression models and the data sources is given in Section 3. The main insights are summarized Section 4 and discussed in Section 5.

2. Literature review

There are few studies that are concerned with the electricity sector in Portugal, and to our knowledge there is only one study that has analyzed the Portuguese electricity consumption from an econometric perspective (Carmona, 2006). In his master's thesis, Carmona (2006) uses cointegration techniques to analyze residential electricity consumption between 1957 and 2002. The study found an income elasticity of 1.1, which is in contradiction with the literature where electricity consumption is usually found to be price inelastic. The value for Portugal was obtained without having other control variables in the model and is, therefore, a simple and possibly biased estimate.

Ferreira et al. (2007) provide an analysis of the Portuguese electricity market from a regulatory and economic perspective. They find that although the electricity market was liberalized in 2004 it is still strongly dominated by one player, Energias de Portugal (EDP). Also they point out that in practice the final consumer could not choose the provider freely until September 2006.

Due to its particular geography, Portugal has a large potential for solar, wind and wave energy. There are a number of studies that approach the topic from an engineering perspective and analyze the potential for electricity production from renewable sources and also nuclear power (Estanqueiro et al., 2008; Mollison and Pontes, 1992; Gomes, 2008).

On the international stage, residential energy consumption is a heavily studied subject. There is a large body of literature that has recently been summarized by Swan and Ugursal (2009) in a comprehensive review. The reviewed studies are divided into top-down and bottom-up studies, based on the level of aggregation of the data that is used. Since we analyze electricity consumption in Portugal at two scales, this distinction is relevant for our case and we adopted it, but with a focus on electricity.

Top-down studies often use time-series data that is aggregated to the national or regional scale to estimate price and income elasticities of electricity demand. Typically, the per capita electricity consumption is regressed on its own price, the price of a substitute for electricity and a measure of income such as gross domestic product. Due to data constraints the use of other control variables is limited and the only variables that are sometimes included are climate (degree-days) and the level of urbanization. For example, Halicioglu (2007) studies residential electricity consumption in Turkey using a cointegration approach (autoregressive distributed lag, ARDL). The estimated model relates the natural logarithm of per capita residential electricity consumption with income per capita, price and the level of urbanization. The level of urbanization is proposed as a measure of economic development and an increased urbanization has been found to drive energy consumption up. A series of other studies have used very similar methodologies to estimate price and income elasticities for residential electricity demand (Holtedahl and Joutz, 2004; Narayan and Smyth, 2005; Dergiades and Tsoulfidis, 2008; Amusa et al., 2009). The first international comparison of price elasticities has recently been published by Azevedo et al. (in press) using panel data methods and testing different model specifications. In all the studies cited there, the short-run elasticity is found to be smaller than the long-run elasticity and most of the studies find that electricity consumption is price and income inelastic.

The studies using a bottom-up approach have more diverse goals and methodologies, but at that scale data is mostly cross-sectional and time-series data is scarce. Micro-scale electricity consumption data is usually collected in surveys or measured directly. In contrast to the literature that uses a top-down approach, multivariate analysis is still rather scarce in bottom-up analysis. Poulsen and Forrest (1988) point out that using multivariate regression techniques enable the importance of income to be disaggregated from other socioeconomic and dwelling characteristics. They observe that dwelling size and family structure are significant determinants of consumption. A more recent example for multivariate analysis using survey data is given in Filippini and Pachauri (2004). In agreement with the literature at the aggregated scale, their findings show that the short-run elasticity is smaller than the long-run elasticity. Dwelling characteristics, demographic and geographical variables are found to be significant. An analysis where data is directly measured is Yohanis et al. (2008). For this study the consumption profiles of 27 households in the UK have been measured in half hour intervals during a period of three months. The profiles are analyzed visually and with bivariate statistics, but in this study multivariate analysis is left aside. The dwelling characteristics, number of appliances and demographics of its inhabitants are identified as important determinants of consumption.

The examples provided above represent the most recent advancements in studies concerned with residential electricity consumption. Studies using top-down or bottom-up approaches have similar goals since their main focus is to estimate price and income elasticities of demand. At the aggregated level there is usually good historic data that allows the price elasticities of electricity demand to be identified. However, due to data availability, the number of variables in aggregated studies is quite limited. For studies at the individual household level this is different. The data usually exhibits more detailed information about the households and the dwellings. The disadvantage of bottom-up data is that it is often cross-sectional and, therefore, studying the influence of changes in price on consumption is more difficult.

3. Model and data specification

We analyze the electricity consumption of the residential sector in Portugal at two different scales. One part uses data that is aggregated by municipality for the year 2001 (top-down), and the other part uses the latest Portuguese consumer expenditure survey from 2005 and 2006 (bottom-up). The unit of analysis in the aggregated case is the municipality and in the other case, it is the individual household. Our study area is the Portuguese mainland, which is inhabited by approximately 10 million people and consists of 278 municipalities. The map in Fig. 1 shows the geography of the study area and the consumption of electric energy per capita by municipality. In Portugal, the population, as well as the economic activity, are strongly concentrated in the metropolitan areas of the two largest cities, Lisbon and Porto. In terms of urban density and economic development, these major metropolitan regions are very different from the rural areas.

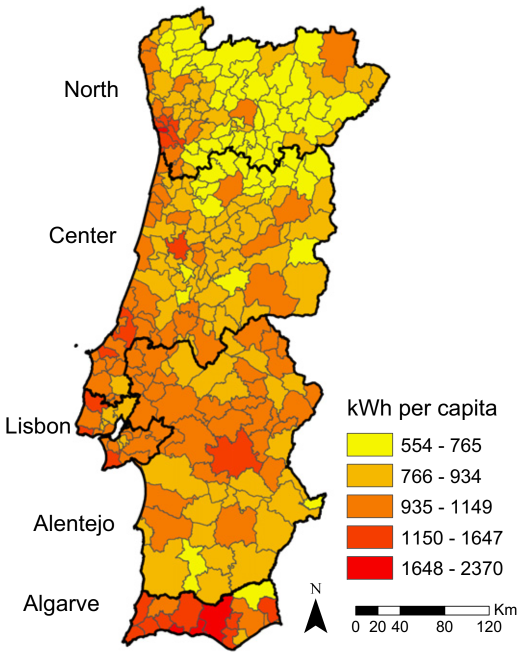

Fig. 1. Map of our study area, mainland Portugal, showing the electricity consumption per capita in 2001 for each of the 278 municipalities. The five statistical regions that are designated in the survey data are marked on the map.

3.1. Model specification

Although the level of detail of the data is not the same for the two scales, the models at both levels are chosen such that they are comparable. We use ordinary least squares (OLS) regression to estimate all the model coefficients and the dependent variable at both scales is the natural logarithm of electricity consumption per capita. The definition of all the variables used at both scales is given in Table 1. For both scales of analysis we included measures of income, the number of people per household and the age of the dwelling. For the bottom-up analysis we also included the number of appliances in the household, a dummy variable for the presence of children in the household, a dummy variable for the occupancy type, the floor area, the dwelling type, the level of urbanization and dummy variables for different regions. Previous studies have identified many of these variables as important determinants of electricity consumption (Filippini and Pachauri, 2004; Halicioglu, 2007).

Information at the municipality level is more scarce. The size of the dwellings, the construction type, appliance ownership and the level of urbanization are not directly available at the aggregated level for Portugal. As an alternative solution in this situation we use proxies for these characteristics. We propose the use of the average number of dwellings per building to be a substitute for the dwelling type. Similarly, we propose to use the average number of rooms per dwelling as a proxy for the total floor area of the dwellings. To account for different levels of urbanization we propose to use dwelling density. Climate and regional effects are also included in the analysis. Unfortunately we did not find a possible substitute for appliance ownership.

The choice of the specific functional form to describe electricity consumption is somewhat arbitrary. Although there is a convergence in the literature towards logarithmic models, there is no real consensus about the best functional form. Different studies use different specifications: Poulsen and Forrest (1988) assume a linear relationship, Filippini and Pachauri (2004) assume a logarithmic relationship and a mixture of both is assumed by Halicioglu (2007). For the sake of completeness we, therefore, estimate both a basic semi-logarithmic model (1a and 2a) and a double-logarithmic model (1b and 2b) for the two scales of analysis. The equations for all of the models we estimate in this study and the definition of the variables are given in Table 1.

For each scale we also estimated an additional model. The significance levels of the variables in the two top-down models 1a and 1b vary slightly and therefore we included one model that has the highest R-squared and significance levels of the variables we could find (Model 1c). In order to show the incremental change of average consumption related to the family size, we estimate one additional model at the household level (Model 2c). Instead of treating the number of people per household as a continuous variable we create dummies for the different sizes and estimate the corresponding coefficients. This allows to further resolve the change in electricity consumption as a function of the family size.

3.2. Data sources and description

Most of the data on the characteristics of the municipalities for the top-down models was retrieved from the online database of the Portuguese statistical office, Instituto Nacional de Estatística (INE). Demographics of the population and dwelling characteristics originate from the Portuguese census (INE, 2003) and were collected from INE's online database (INE, 2010). Yearly residential electricity consumption data per municipality is collected by the Ministry of Economy and Innovation and published online

Table 1
Model specification and variable definitions.

Top-down variables	Unit	Abbrev.	Bottom-up variables	Unit	Abbrev.
Income (average wage)	10^3 €/month	*inc*	Income (total household income)	10^3 €/month	*inc*
Persons per household		*pph*	Persons per household		*pph*
–			Nr. of appliances		*app*
–			Children	dummy	*chi*
–			Occupancy type	dummy	*own*
Building age	10 years	*age*	Building age	10 years	*age*
Rooms per dwelling		*rpd*	Dwelling area	10 m^2	*am2*
Dwellings per building		*dpb*	Dwelling type (ref. Detached)	dummy	*dwt*
Dwelling density	10^3/km^2	*dwd*	Urbanization level (ref. Rural)	dummy	*urb*
Heating degree-days	10^3 °C · days	*hdd*	Region (ref. North)	dummy	*reg*
Cooling degree-days	10^3 °C · days	*cdd*			
Latitude		*lat*	–		
Longitude		*lon*	–		

Scale & Model	Equation
Municipalities	
1a Basic	$ln(E)=\beta_0+\beta_1 inc+\beta_2 pph+\beta_3 age+\beta_4 rpd+\beta_5 dpb+\beta_6 dwd+\beta_7 hdd+\beta_8 cdd+\beta_9 lat+\beta_{10} lon+\epsilon$
1b Elasticities	$ln(E)=\beta_0+\beta_1 ln(inc)+\beta_2 ln(pph)+\beta_3 ln(age)+\beta_4 ln(rpd)+\beta_5 ln(dpb)+\beta_6 ln(dwd)+\beta_7 ln(hdd)+\beta_8 ln(cdd)+\beta_9 ln(lat)+\beta_{10} log(lon)+\epsilon$
1c Best fit	$ln(E)=\beta_0+\beta_1 ln(inc)+\beta_2 ln(pph)+\beta_3 age+\beta_4 rpd+\beta_5 dpb+\beta_6 ln(dwd)+\beta_7 hdd+\beta_8 cdd+\beta_9 lat+\beta_{10} lon+\epsilon$
Households	
2a Basic	$ln(E)=\beta_0+\beta_1 inc+\beta_2 pph+\beta_3 app+\beta_4 chi+\beta_5 own+\beta_6 age+\beta_7 am2+\sum_{i=8}^{11}\beta_i dwt_i+\sum_{i=12}^{13}\beta_i urb_i+\sum_{i=14}^{17}\beta_i reg_i+\epsilon$
2b Elasticities	$ln(E)=\beta_0+\beta_1 ln(inc)+\beta_2 ln(pph)+\beta_3 ln(app)+\beta_4 chi+\beta_5 own+\beta_6 ln(age)+\beta_7 ln(am2)+\sum_{i=8}^{11}\beta_i dwt_i+\sum_{i=12}^{13}\beta_i urb_i+\sum_{i=14}^{17}\beta_i reg_i+\epsilon$
2c Incremental	$ln(E)=\beta_0+\beta_1 ln(inc)+\sum_{i=2}^{6}\beta_i pph_i+\beta_7 ln(app)+\beta_8 chi+\beta_9 own+\beta_{10} ln(age)+\beta_{11} ln(am2)+\sum_{i=12}^{15}\beta_i dwt_i+\sum_{i=16}^{17}\beta_i urb_i+\sum_{i=18}^{21}\beta_i reg_i+\epsilon$

by INE (2010). All variables describing the municipalities, except income, have been obtained for the year 2001. Income is measured as the average monthly wage of workers in each municipality, which is only published biannually and therefore the values for income are from 2002. The variables for heating and cooling degree-days were derived from the Global Surface Summary of the Day (GSOD) database, as described later in this section. The variation and spatial distribution of each variable on the top-down level is illustrated in a map in the Electronic Annex A in the online version of this article.

The data source for the bottom-up analysis is the Portuguese consumer expenditure survey (INE, 2008). The survey contains a sample of 7925 households in the Portuguese mainland. It has been collected by INE as a representative stratified clustered sample during the period between October 2005 and October 2006.[1] The weighting of each observation according to the stratification and clustering of the data has been taken into account in the calculations of the summary statistics as well as for the estimation of the regression models. We used taylor linearized variance estimators to estimate the standard errors from the OLS estimates.

In the survey, income is measured as the total monthly monetary household income. The dummy variable for the presence of children is 1 if children are present and 0 otherwise. Similarly the type of occupancy is 1 if the dwelling is owned by a member of the household and 0 otherwise. The categories for the dummy variables for the dwelling type are detached house (reference category), semi-detached house, apartment in a building with less than 10 apartments, apartment in a building with more than 10 buildings and other type of dwelling. The categories for the level of urbanization are rural (reference category), half-urban and mainly urban. The regions we controlled for are North (reference category), Center, Lisbon, Alentejo and Algarve. Due to confidentiality reasons it was not possible to obtain a more detailed spatial encoding of the households. The five regions are marked on the map in Fig. 1. The categories for the size of the family in Model 2c are a stepwise increase from one person per household (reference category) up to six or more persons per household.

Descriptive statistics of all the variables at both levels of aggregation are shown in Table 2. Note that the average values at the municipality level are not directly comparable to values at the household level. The large difference in the average electricity consumption has two reasons: on the one hand, the year of analysis is not the same in the two cases. Between 2001 and 2006 there was an increase of 240 kWh/capita in consumption of electricity in mainland Portugal. The 2001 residential consumption of electricity was 1038 kWh/capita, whereas in 2006 it was 1278 kWh/capita. On the other hand the average shown in Table 2 are obtained from averaging over municipalities. The averaging of the values over the municipalities, however, result in a different value than averaging over population because the municipalities do not all have the same population. Table 2 summarizes the data as it is used for the regression, resulting in an average of 922 kWh/capita over the municipalities.

In both years of analysis, electricity prices for the final consumer in the residential sector have been regulated. Although the electricity market for the final consumer in the residential sector has formally been liberalized in 2004, the individual consumer has not yet had the possibility to choose its provider freely before September 2006 (Ferreira et al., 2007). All the residential consumers were still under the regulated market for both years of analysis. This implies that for this study the electricity pricing system is the same over the whole study area. For the analysis at the municipality level, prices can, therefore, be left aside without introducing a bias. As a consequence, it was not possible to estimate the price elasticity of electricity consumption in this study. The same considerations are also true at the household level. The survey contains the total expenditure per household for electricity in monetary units. To convert the expenditure into units of energy we used the average price of electricity in 2006 of 0.141 €/kWh (Eurostat, 2007).

As a way to cross-validate the data from both scales, we compared the estimates of average electricity consumption from the survey data with published consumption data. From the same

[1] The technical documentation of the survey can be found under http://www.ine.pt/ngt_server/attachfileu.jsp?look_parentBoui=27974452&att_display=n&att_download=y

Table 2
Summary statistics for the variables at both scales. There are 278 municipalities in our study area and the survey data consists of 7925 households in mainland Portugal. Note that to compare the averages on the two levels of analysis the differences in year and the scale of analysis has to be taken into account (see also Section 3.2).

Scale, Year & Variable	Mean	Std. Dev.
Municipality Level, 2001		
kWh per capita	922.19	239.37
Income (1000 €)	0.59	0.10
People per household	2.75	0.25
Building age (10 yr)	3.38	0.52
Rooms per dwelling	4.76	0.32
Dwellings per building	1.34	0.57
Dwelling density (1000)	0.07	0.11
Heating degree-days (1000)	2.21	0.6
Cooling degree-days (1000)	0.31	0.1
Latitude	1.58	0.26
Longitude	1.42	0.20
Household Level, 2005/06		
kWh per capita	1386.87	1155.17
Income (1000 €)	1.50	1.50
People per household	2.75	1.24
Nr. of appliances	14.04	5.42
Children[a]	0.58	0.49
Owner[a]	0.50	0.50
Dwelling area (100 m^2)	1.07	0.54
Building age (10 yr)	3.29	2.37
Rural[a]	0.13	0.34
Semi urban[a]	0.15	0.36
Mainly urban[a]	0.72	0.45
Detached house[a]	0.40	0.49
Semi-detached house[a]	0.22	0.41
Apt. building <10[a]	0.21	0.40
Apt. building >10[a]	0.17	0.38
Building other[a]	0.01	0.09
North[a]	0.35	0.48
Algarve[a]	0.04	0.20
Central[a]	0.24	0.43
Lisbon[a]	0.29	0.45
Alentejo[a]	0.08	0.27

[a] Dummy variables.

Table 3
Cross validation of the two data sources by region: consumption data from 2006 as published by INE and calculated values from the survey data. All values are given in kWh/capita.

Region	INE	Survey	Difference (%)
Mainland PT	1278	1387	9
North	1251	1356	8
Center	1207	1379	14
Lisbon	1268	1432	13
Alentejo	1268	1302	3
Algarve	2001	1530	−24

source as for the municipal consumption in the top-down analysis (INE, 2010), we retrieved regional consumption data for the year 2006. For each of the five regions that are specified in the survey data, as well as for the whole study area, we compared the survey estimates with the aggregate values. Table 3 summarizes this comparison, showing a difference of 9% over the whole study area. The differences are consistent with the survey design that targeted an error in the total household expenditure of 10% in the two more important regions Lisbon and North, and 20% in the other regions (INE, 2008). Since these errors were specified on the total spending, the errors on one specific expenditure such as electricity will tend to be slightly larger.

To include climate related effects in the top-down approach, we analyzed the Global Surface Summary of the Day (GSOD) database (NCDC, 2011). It contains daily average temperature measurements for each station in the database. Within the portuguese mainland, the GSOD contained 20 weather stations that have at least half a year worth of data in 2001. The data for these stations was converted into yearly heating and cooling degree-days using a base temperature of 20 °C. In a next step, the twenty point measurements of degree-days were interpolated to a smooth surface using the Kriging interpolation tool in ArcGIS 9.3. Finally the average number of heating and cooling degree-days was computed for each municipality by computing zonal statistics of that surface.

To capture other regional effects in the top-down approach we included the latitude and longitude of the centroid of each municipality in normalized coordinates. In these coordinates both latitude and longitude range from 1 to 2, where the value (1,1) stands for the most south-western municipality and the value (2,2) for the most north-eastern. In the survey data the spatial encoding is very rough, it is only specified to the level of five statistical regions: North, Center, Lisbon, Alentejo and Algarve. We include dummy variables for these regions to control for regional and climate effects. The five regions are designated in Fig. 1.

The original form of the census data at the municipality level, consisted of variables measured by several discrete categories. Average values for each variable and each municipality were obtained using counts from these discrete categories.[2] This calculation was performed for the following variables: persons per household, building age, rooms per dwelling and dwellings per building. Due to the strong collinearity between counts in the different categories, it was not possible to use the counts directly in the regression.

Six of the municipalities in our study area have a high consumption level of electricity per capita. These cases are outliers, and the regression including these cases suffers from heteroskedasticity and non-normal errors. We, therefore, used the Huber and White heteroskedasticity robust standard errors. Additionally, we also tested a model where these cases were excluded and another model where they where tagged with dummy variables. After removing the outliers all Gauss–Markov assumptions, which are needed for an unbiased and efficient OLS regression, are satisfied and the signs of the estimates do not change. Removing the outliers does not remove the significance of the estimates. The estimates that are obtained using dummy variables for high consumption are similar to the basic model. Therefore, we considered the basic model using the full data set with heteroskedasticity robust standard errors as stable and only show the results of that version.

The electricity consumption per capita of the individual households is not perfectly normal distributed. Taking the logarithm of the variable has brought the distribution close to normal, but a small skewness of 0.7 and a kurtosis of 4.8 remained in the data.

4. Results

The results from the top-down estimation are presented in Table 4 and the bottom-up results are presented in Table 5. In general the results from both scales are consistent between each other and in good agreement with the literature. All the coefficients that are statistically significant have the same

[2] For example, the categories for persons per household (pph) were: 1 pph, 2 pph,..., 9 pph, 10 or more pph.

Table 4
Estimation results from OLS regression at the municipality level.

Variable	Model 1a Basic	Model 1b Elasticities	Model 1c Best Fit
Income	0.3366*	0.2115**	0.2719***
	(0.145)	(0.081)	(0.077)
People per household	−0.1225*	−0.7623***	−0.8795***
	(0.050)	(0.179)	(0.165)
Building age	−0.1378***	−0.2243*	−0.0718*
	(0.031)	(0.113)	(0.031)
Rooms per dwelling	0.0525	0.3714	0.0270
	(0.035)	(0.192)	(0.035)
Dwellings per building	−0.1333***	−0.1239	−0.1438***
	(0.034)	(0.094)	(0.031)
Dwelling density	1.0633***	0.1213***	0.1583***
	(0.125)	(0.029)	(0.026)
Heating degree-days	−0.1203**	−0.4541***	−0.1867***
	(0.044)	(0.136)	(0.046)
Cooling degree-days	−0.1077	−0.0984	−0.2868*
	(0.129)	(0.057)	(0.132)
Latitude	−0.3769***	−0.3772**	−0.3150***
	(0.090)	(0.142)	(0.088)
Longitude	0.0924	0.4333*	0.3616**
	(0.098)	(0.197)	(0.128)
Constant	8.0240***	8.0533***	9.1567***
	(0.298)	(0.437)	(0.320)
R-squared	0.521	0.527	0.567
Nr. of cases	278	278	278
F	22.718***	17.882***	22.085***

*$p<0.05$, **$p<0.01$, ***$p<0.001$.

Table 5
Estimation results from OLS regression at the household level.

Variable	Model 2a Basic	Model 2b Elasticities	Model 2c Incremental
Household characteristics			
Income	0.0497***	0.1282***	0.1274***
	(0.007)	(0.013)	(0.013)
People per household	−0.2903***	−0.8303***	
	(0.009)	(0.022)	
Nr. of appliances	0.0294***	0.4051***	0.4070***
	(0.002)	(0.024)	(0.025)
Children	0.0870***	0.0595**	0.0389
	(0.022)	(0.021)	(0.023)
Owner	0.0629***	0.0621***	0.0594***
	(0.016)	(0.016)	(0.016)
Dwelling characteristics			
Area of dwelling	0.1369***	0.1668***	0.1680***
	(0.016)	(0.019)	(0.019)
Building age	−0.0113***	−0.0159	−0.0154
	(0.003)	(0.011)	(0.011)
Dwelling type (ref. Detached house)			
Semi-detached hose	0.0130	0.0060	0.0046
	(0.019)	(0.019)	(0.019)
Apt. building <10	−0.0258	−0.0497*	−0.0523*
	(0.023)	(0.022)	(0.022)
Apt. building >10	−0.0434	−0.0659*	−0.0659*
	(0.026)	(0.026)	(0.026)
House other	−0.0945	−0.0176	−0.0146
	(0.102)	(0.104)	(0.103)
Urbanization (ref. Rural)			
Semi-urban	0.0981***	0.0819***	0.0842***
	(0.025)	(0.024)	(0.024)
Mainly urban	0.1828***	0.1589***	0.1593***
	(0.022)	(0.022)	(0.022)
Region (ref. North)			
Central	−0.0435*	−0.0497**	−0.0512**
	(0.018)	(0.018)	(0.018)
Lisbon	−0.1203***	−0.1335***	−0.1354***
	(0.022)	(0.021)	(0.021)
Alentejo	−0.0681***	−0.0782***	−0.0777***
	(0.020)	(0.020)	(0.020)
Algarve	−0.0329	−0.0451*	−0.0444*
	(0.020)	(0.020)	(0.020)
Household size (ref. 1 person)			
2 Persons			−0.5285***
			(0.022)
3 Persons			−0.8974***
			(0.029)
4 Persons			−1.1783***
			(0.035)
5 Persons			−1.3033***
			(0.043)
6 or more Persons			−1.5469***
			(0.059)
Constant	7.0605***	5.0127***	5.0071***
	(0.049)	(0.115)	(0.114)
R-squared	0.322	0.344	0.345
Nr. of cases	7925	7925	7925
F	138.5***	159.4***	129.7***

*$p<0.05$, **$p<0.01$, ***$p<0.001$.

expected sign at both levels of analysis. In terms of the R-squared the top-down models exhibit a better goodness of fit than the bottom-up models and at each scale the three models have similar predictive power. The coefficients in the double-logarithmic models (1b and 2b) are more comparable to each other because elasticities do not depend on the scale of the variables.

The results show that an increase in income, appliance ownership and floor area result in a higher per capita electricity consumption. Furthermore, there are clear economies of scale for households, as families with more members consume less electricity per capita. This is visible in Model 2c where the stepwise incremental decrease of per capita consumption with increasing household size is shown explicitly. People living in single family houses consume more electricity than people living in multi-family houses or apartments. Urban households consume more electricity per capita than rural households.

The 95% confidence intervals of the income elasticities from the Models 1b and 2b overlap and thus the two estimates are consistent in this regard. Nevertheless there is a difference of a factor of 2 between the two estimates. The income elasticity in the top-down analysis is 0.212, whereas it is 0.128 in the bottom-up case.

The significance levels of the coefficients for the number of people per household and dwellings per building depend on the model specification. This motivated the estimation of Model 1c, which has the combination with the highest explanatory power, where the logarithmic form is mixed with the linear one. Two of the proxies for the dwelling characteristics are significant and have the expected sign. Only the number of rooms per dwelling is not significant in any of the estimated models and is, therefore, not an useful proxy for the area of the dwelling in Portugal.

In the top-down models regional and climate effects were significantly related to electricity consumption. In regions with more heating degree-days households consume less electricity per capita than those in more moderate climates. Households that are located in the northern part of the country and more eastward tend to consume less electricity per capita on average that their counterparts in the South and along the west coast.

5. Discussion

We have studied residential electricity consumption in Portugal at two different scales: first at an aggregated level by municipality and second at a micro-scale level by individual households. This is an innovative approach as it is the first time

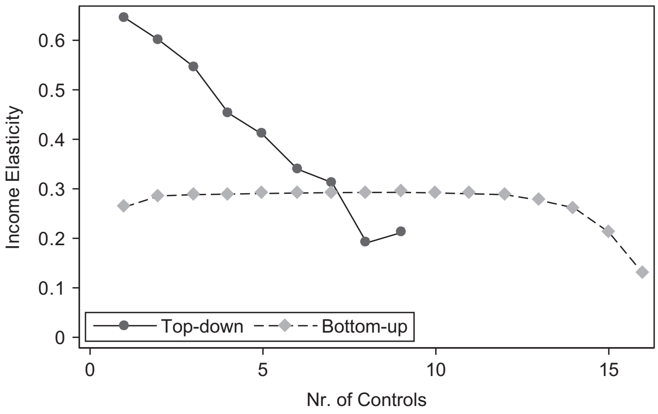

Fig. 2. The change in elasticity when increasing the number of controls, showing the decrease in the income elasticity estimate. The additional control variables have a stronger effect on the elasticity at the top-down level.

that residential electricity consumption has been compared using a top-down and a bottom-up perspective in the same study.

The good agreement of the results at both levels of analysis are encouraging because they provide evidence that supports the validity and comparability of both approaches. Although the comparability of the specific values of the estimates is limited due to the differences in the definition of the variables, the signs are the same for all statistically significant estimates.

Two out of three of the proxies for the building characteristics in the top-down approach were statistically significant and had the same sign as their corresponding value in the bottom-up models. Thus they can be regarded as a valid substitute of the characteristics of the individual dwellings and their surroundings. These variables could be used in future studies at the aggregated level and would increase the reliability of the estimated parameters.

At both levels of analysis residential electricity demand in Portugal is income inelastic and the estimated elasticities are relatively low. Furthermore, the elasticity is substantially smaller in the bottom-up approach where more control variables have been included. This suggests that the direct effect of income on consumption of electricity is low, once control variables for the type of household and dwelling, as well as for the appliances in the household are introduced. This tendency is illustrated in Fig. 2 where the income elasticity is plotted for different numbers of control variables. The plot shows estimates from Models 1b and 2b by sequentially introducing the control variables, ordered according to their impact on elasticity. In each step the variable that was added out of the remaining variables, was the one that resulted into the highest value for the elasticity in that step. The graph shows a tendency where the income effect becomes smaller as more control variables are included, specially in the top-down approach. Without controlling for other determinants of electricity consumption, income elasticity partly captures the effect of these control variables and the direct effect of income on electricity consumption in Portugal is likely to be overestimated.

Our results indicate that policy measures that only take into consideration the income of households in Portugal might not be as effective as expected. The importance of the demographic structure of the population and the characteristics of the dwellings and their equipment should be taken into account. Clearly some of the measured variables such as the size of the household can not be influenced directly by policy. They can, therefore, not be directly used to design policies. Nevertheless their trends have to be taken into consideration when the goals of a policy are formulated since they have a strong impact on demand. The future trend of electricity consumption in Portugal will not only be influenced by the total population and income, but also by demographic factors and changes in the building stock of the country.

Acknowledgments

This research was funded in parts by the MIT-Portugal Program and the Center for Climate and Energy Decision Making (CEDM). The CEDM has been created through a cooperative agreement between the National Science Foundation (SES-0949710) and Carnegie Mellon University. The authors thank the financial support from Fundação para a Ciência e Tecnologia through the doctoral grant SFRH/BD/42964/2008. We are specially thankful to Professor Emilio Castilla for his important comments on early versions of this work as well as to Professor Isabel Proença for her help on methodological issues. For their valuable comments on a later draft we also thank David Quinn, Cristina Carias, Ana Venâncio and Rodrigo Belo. Finally we also thank the anonymous reviewers for their helpful comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2011.02.047.

References

Amusa, H., Amusa, K., Mabugu, R., 2009. Aggregate demand for electricity in south africa: an analysis using the bounds testing approach to cointegration. Energy Policy 37, 4167–4175.

Azevedo, I.M.L., Morgan, M.G., Lave, L. Residential and regional electricity consumption in the U.S. and EU: How much will higher prices reduce CO2 emissions? The Electricity Journal, in press, doi:10.1016/j.tej.2010.12.004.

Bielecki, J., 2002. Energy security: Is the wolf at the door? The Quarterly Review of Economics and Finance 42, 235–250.

Carmona, N.M., 2006. Modelação econométrica da procura de electricidade em Portugal continental: uma aplicação empírica. Master thesis, Technical University of Lisbon, Instituto Superior de Economia e Gestão, Lisbon.

Dergiades, T., Tsoulfidis, L., 2008. Estimating residential demand for electricity in the United States, 1965–2006. Energy Economics 30, 2722–2730.

DGEG, 2010. Estatísticas—Energia Eléctrica, Direcção Geral de Energia e Geologia. http://www.dgge.pt/.

DGEG, 2011. Estatísticas—Indicadores Energéticos, Balanço Energético Nacional 2009 (provisório), Direcção Geral de Energia e Geologia. http://www.dgge.pt/.

Estanqueiro, A., Castro, R., Flores, P., Ricardo, J., Pinto, M., Rodrigues, R., Peças Lopes, J., 2008. How to prepare a power system for 15% wind energy penetration: the portuguese case study. Wind Energy 11, 75–84.

Eurostat, 2007. Gas and electricity market statistics. Statistical Office of the European Communities.

Eurostat, 2009a. Energy, transport and environment indicators. Statistical Office of the European Communities.

Eurostat, 2009b. Panorama of Energy. Statistical Office of the European Communities.

Fankhauser, S., Tepic, S., 2007. Can poor consumers pay for energy and water? An affordability analysis for transition countries. Energy Policy 35, 1038–1049.

Ferreira, P., Araújo, M., O'Kelly, M., 2007. An overview of the portuguese electricity market. Energy Policy 35, 1967–1977.

Filippini, M., Pachauri, S., 2004. Elasticities of electricity demand in urban indian households. Energy Policy 32, 429–436.

Gomes, J.F.P., 2008. Reflections on the use of renewable power sources and nuclear energy in Portugal. International Journal of Environmental Studies 65, 755.

Halicioglu, F., 2007. Residential electricity demand dynamics in Turkey. Energy Economics 29, 199–210.

Holtedahl, P., Joutz, F.L., 2004. Residential electricity demand in Taiwan. Energy Economics 26, 201–224.

INE, 2003. Censos—Antecedentes, metodologias e conceitos—2001. Instituto Nacional de Estatística, Portugal.

INE, 2008. Inquérito às Despesas das Famílias 2005-2006. Instituto Nacional de Estatística, Portugal.

INE, 2010. Online database, Instituto Nacional de Estatística, Portugal. 〈http://www.ine.pt/〉.

IPCC, 2007. Climate change 2007—the physical science basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Mollison, D., Pontes, M., 1992. Assessing the portuguese wave-power resource. Energy 17, 255–268.
Narayan, P.K., Smyth, R., 2005. The residential demand for electricity in australia: an application of the bounds testing approach to cointegration. Energy Policy 33, 467–474.
NCDC, 2011. Global Surface Summary of the Day-GSOD, National Climatic Data Center, NESDIS, NOAA, U.S. Department of Commerce. ⟨http://gcmd.nasa.gov/records/GCMD_gov.noaa.ncdc.C00516.html⟩.
Niza, S., Ferrão, P., 2006. A transitional economy's metabolism: the case of Portugal. Resources, Conservation and Recycling 46, 265–280.
Poulsen, M.F., Forrest, J., 1988. Correlates of energy use: domestic electricity consumption in sydney. Environment and Planning A 20, 327–338.
Presidência do Conselho de Ministros, 2010. Resolução do Conselho de Ministros N.º 29/2010, Diário da República 1.ª série N.º 73.
Swan, L.G., Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renewable and Sustainable Energy Reviews 13, 1819–1835.
Umbach, F., 2010. Global energy security and the implications for the EU. Energy Policy 38, 1229–1240.
UNFCCC, 2010. Kyoto Protocol. United Nations Framework Convention on Climate Change. ⟨http://unfccc.int/kyoto_protocol/items/2830.php⟩.
Yohanis, Y.G., Mondol, J.D., Wright, A., Norton, B., 2008. Real-life energy use in the UK: how occupancy and dwelling characteristics affect domestic electricity use. Energy and Buildings 40, 1053–1059.