UNIVERSITY OF GOTHENBURG

Determinants of Energy Demand for Heating in the European Residential Sector

Master's Thesis in Economics

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Abstract

The improvement of energy efficiency is one of the key targets of EU energy policy. In order to design and implement efficient energy policy, information on energy demand price and income elasticities is required. This thesis puts forward a stylized theoretical model of residential energy demand and empirically examines space heating demand from 1990 to 2015 in six European countries (France, Germany, Italy, Spain, Sweden, and the UK). By use of dynamic panel data models, the short-run and long-run price elasticities for space heating are estimated to -0.21 and -0.44 respectively, suggesting an inelastic demand with some room for discouraging energy consumption using price increases. The corresponding income elasticities are estimated to 0.16 and 0.43. The elasticities are smaller for electricity demand and robust over estimation techniques. The inclusion of additional sets of variables into the model suggests that energy performance standards and financial incentives also play important roles in promoting energy savings, whereas informative measures do not yield a significant impact.

Keywords: Residential energy demand; Space heating; Energy policy
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List of Acronyms

EC	European Commission
EU ETS	European Union Emission Trading Scheme
FE	Fixed Effects
GMM	Generalized Method of Moments
HDD	Heating Degree Days
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LSDVC	Least Square Dummy Variable Corrected
NEEAP	National Energy Efficiency Action Plan
UEDT	Underlying Energy Demand Trend
WAP	Weighted Average Price

1 Introduction

The building sector represents the largest energy-consuming sector in the economy, ahead of transportation and industry. This sector accounts for over one-third of all final energy and half of global electricity consumption (IEA, 2017). The European Commission has stated that the greatest potential for reducing anthropogenic greenhouse gas emissions lies in buildings and, in the European Union, they account for over 36 percent of the emissions (EC, 2010, 2018). Most buildings can be found in the residential sector, where the cost-effective potential for energy savings from improved efficiency is estimated at around 30 percent (EC, 2006). On the basis of this, the European Commission highlights improving energy efficiency as one of the most cost-effective ways of reducing greenhouse gas emissions, increasing security of energy supply, and enhancing industry competitiveness (EC, 2010). The EU Climate and Energy Framework proposes a 27 percent improvement in energy efficiency by 2030. The realization of this target would further help the EU in achieving its commitments in the Paris Agreement to limit anthropogenic global warming to 'well below' two degrees Celsius.

A number of policy measures are currently in use or are being considered in many locations within the EU to help encourage energy efficiency investments or energy conservation in the residential sector. These measures include, among others, price increases through the introduction or increase of energy taxes, mandatory performance standards of buildings, and subsidies to promote energy-saving buildings. To design and implement efficient energy policy, information on energy demand is required. This thesis aims to identify the relationship between residential energy demand for space heating and several demand determinants, including price, income, and energy efficiency measures.

In particular, this thesis addresses four main research questions. First, what are the short-run and long-run price and income elasticities of the residential energy demand for space heating? Second, how do the elasticities of energy demand for space heating compare to those of total energy demand and electricity demand? Third, is there evidence of bias in elasticity estimates due to correlation between the lagged energy consumption level and the error term? Fourth, which energy efficiency measures are most effective in reducing energy demand for space heating?

To answer these questions, a unique panel dataset with information on annual residential energy consumption at the country level for the period 1990 to 2015 in six European countries is used. The selected countries are France, Germany, Italy, Spain, Sweden, and the United Kingdom which together account for more than 70 percent of EU energy demand for space heating (Enerdata, 2018b). The demand equation is derived using a stylized framework of household production theory, and a partial adjustment model is estimated. Three separate estimation techniques suited for dynamic panel models are employed. The primary dependent variable is the log energy use for space heating and the regressors, in addition to the lagged dependent variable, include the log transformations of the weighted average price (WAP) of energy, income, and other controls.

Most of the previous empirical literature on residential energy demand has focused only on the electricity component of demand. However, electricity for lighting and electrical appliances accounts for less than 14 percent of total residential energy demand while space heating accounts for more than 65 percent (Enerdata, 2018b). In addition, energy demand for space heating is argued to be driven by rather different forces of consumption than electricity demand (Brounen, Kok, & Quigley, 2012). Despite this, only three studies exist that examine energy demand for space heating using aggregated data. Two of them was not able to explore the dynamic nature of energy demand (Saussay, Saheb, & Quirion, 2012; Ó Broin, Nässén, & Johnsson, 2015a), and the third (Ó Broin, Nässén, & Johnsson, 2015b) faced data limitations and failed to control for unobserved heterogeneity between countries and possible endogeneity issues with the lagged dependent variable. The lack of more empirical research is likely due to the lack of data. The present study utilizes data on energy consumption for space heating that has recently become available as a result of the advent of the Odyssee Database (Enerdata, 2018b).

The effect of a pricing policy is to a large extent determined by the price elasticity of demand for energy, while future energy demand growth is to a large extent determined by the income elasticity of demand. For the estimation of these elasticities, a proper model specification and an appropriate estimation technique are of great importance. In the residential energy demand literature, a large portion of the studies has failed to account for the dynamics of demand. Researchers who have used dynamic adjustment approaches with panel data (e.g. Prosser, 1985; Liu, 2004; Paul, Myers, & Palmer, 2009; Asche, Nilsen, & Tveterås, 2008; Ó Broin et al., 2015b) often control for unobserved heterogeneity using the fixed effects (FE) estimator, sometimes combined with a simple instrumental variable approach. Most of these studies (with the exception of Liu, 2004) fail to recognize and address the possible endogeneity of lagged consumption, which is often included as a regressor on the right-hand side of the demand equation. Hence, the estimated elasticities run the risk of being biased and inconsistent. A wide dispersion of estimates can be observed in the literature and estimated energy demand elasticities have been detected to structurally vary with estimation method (Espey & Espey, 2004). Moreover, existing macro studies have generally been based on data from the 1970s and the 1980s. Though, there is little reason to believe that the same responsiveness observed in periods of rapidly increasing prices (e.g., the 1970s and early 1980s) would hold in periods of more stable energy prices observed in more recent decades (Haas & Schipper, 1998). The present study addresses these issues by i) considering data from 1990 to 2015, and ii) accounting for the possible endogeneity of the FE estimator by the use of more recent econometric techniques.

As previously mentioned, in addition to pricing policies, a number of other measures such as regulatory building standards, financial measures, and informational measures can be considered. From the policymakers' point of view, it is important to have information on the effectiveness of energy policy instruments designed to increase energy efficiency or decrease the level of energy consumed. For instance, one of the interesting questions is whether performance standards or financial incentives are most effective in reducing demand. In fact, during the last two decades, most of the EU member states have introduced performance standards in buildings, heating systems, and electrical appliances in an attempt to improve the level of energy efficiency in the residential sector. Some have also introduced financial incentives such as grants and subsidies. From a research point of view, it is therefore interesting to analyze the impact on energy demand of different energy efficiency policy measures.

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014) has stated that cross-country comparisons of sector-related policies are well warranted. Indeed, literature that seeks to analyze the influence of energy efficiency measures on energy demand is relatively scarce. Hence, the part of this thesis that aims to empirically identify the impact of energy efficiency measures builds upon only a small number of papers. Bigano, Ortiz, Markandya, Menichetti, and Pierfederici (2011) examine the influence of introduced energy efficiency measures on energy intensity. The authors regress the level of energy intensity on several factors such as price, income, and dummy variables representing the presence of energy policy measures. Saussay et al. (2012), in turn, model demand for space heating and include a count variable that represents the number of implemented building standard policies in their model. Filippini, Hunt, and Zorić (2014) develop a dummy variable approach representing both the presence and count of implemented energy efficiency measures for four categories of policy instruments. The latter approach is reconstructed and modified in the present study to account for the fact that building performance standards mostly refer to new buildings. Hence, in addition to building on the work above, the analysis undertaken in this thesis considers a more precise representation of policy instruments to estimate the impact of adopted energy efficiency measures on European energy demand.

In this thesis, the short-run and long-run price elasticities for residential space heating demand are estimated to -0.21 and -0.45 respectively. The corresponding income elasticities are estimated to 0.16 for the short run and 0.34 for the long run. The estimated elasticities are concluded to be larger in absolute terms for space heating demand than electricity demand.

From an energy policy perspective, the results concerning price impacts imply that there is room for discouraging residential energy consumption for space heating using price increases, primarily in the long run. Energy price increases may be attained, for example, by raising energy taxes levied per energy unit sold. A ten percent energy tax is expected to reduce demand by 2.1 percent in the short run. In the long run, the effect is more than doubled, to 4.5 percent. In an energy system mainly based on fossil fuels, price increases may also result from imposing a carbon tax to curb greenhouse gas emissions, or follow from reductions in emission allowances in a cap-and-trade system such as the EU Emissions Trading System (EU ETS).

By holding the time period and the specification the same, the roles of different estimation techniques suited for dynamic panel models are explored. This study employs a fixed effects (FE) ordinary least squared estimator alongside with the Arellano-Bond Generalized Method of Moments (GMM) estimator and a biased corrected estimator referred to as the Least Squares Dummy Variable Corrected (LSDVC). It is found that changing the estimation technique results in only small differences between the elasticity estimates. Indicating that the endogeneity, that comes with the inclusion of lagged energy consumption in the demand equation, does not cause serious problems in the case of this sample.

To provide some evidence of the effectiveness (here defined as effectiveness in reducing energy consumption) of energy efficiency measures implemented in the selected countries, several relevant policy measures are considered in the analysis. The results imply that reductions in energy consumption can be linked to introduced financial incentives and energy performance standards related to buildings or heating systems. Informative measures such as labeling and educational campaigns are not shown to have a significant effect in fostering energy savings. The identified policy effects are furthermore shown to be greater for space heating demand than for electricity demand.

The remainder of this thesis is outlined as follows. In Section 2, a literature review of previous studies regarding residential energy demand is provided. In Section 3, a description of the development of EU energy efficiency measures provides some context. In Section 4, a theoretical model of household demand for space heating is presented. In Section 5, the data are described together with the parameterization of the energy efficiency measures. In Section 6, the construction and specification of a partial adjustment model of energy demand is described and the estimation methods are discussed. In Section 7, the estimation results are presented. Section 8 discusses and Section 9 concludes.

2 Literature Review

This study relates to different strands of literature and builds upon a number of studies on energy demand. The following literature review consists of three parts. First, an overview of the empirical literature on residential demand is provided with an emphasis on price and income effects. This literature mainly investigates electricity demand. This thesis examines both total energy demand and electricity demand, but its main focus lies on space heating demand. Thus, in the second part of the literature review, the few existing studies on space heating demand are discussed. This thesis also investigates the effect on demand of adopted energy efficiency measures. Hence, in the third part, an overview of the studies that attempt to evaluate efficiency policies is provided and their methodological approaches are compared.

2.1 Residential Energy Demand

The body of literature that econometrically examines energy demand in the residential sector is rather extensive. However, it almost exclusively focuses on the electricity part of the demand. The reason for this is likely the availability of data. There exist several early surveys of the empirical residential energy demand literature, e.g. Taylor (1975), Dahl (1993), Madlener (1996), Ferrer-i-Carbonell, Muskens, van Leeuwen, and Velthuijsen (2000). More recently, Espey and Espey (2004) quantitatively summarize short-run and long-run price elasticities of residential electricity demand. From these surveys, it can be observed that the literature has made use of both cross-sectional and panel data. More recently, some studies have made efforts to account for the dynamic nature of energy demand, however many fail to address the possible endogeneity of lagged consumption, which is often included as a regressor on the right-hand side of the demand equation. However, what is clear from the literature is that price and income are key factors influencing demand. Empirical results from the literature regarding both these factors are discussed below.

The relationship between income and energy demand has proved to be a challenge for researchers to map in a precise way; there exists a wide dispersion of results. This is likely due to identification problems. In the early survey by Taylor (1975), the author suggested that the estimated income elasticities from the empirical studies conducted at the time were too unconvincing to be worthy of a summary. The extensive survey performed later by Dahl (1993) concludes that, despite the rather large number of studies up to this point, our understanding of the links between energy demand and income is still quite limited. Likewise, the surveys show substantial variability between elasticity estimates when it comes to price effects on energy demand. Nevertheless, it is clear that, over the long term, households respond to price incentives.

For residential energy demand, Dahl (1993) finds that it is unusual for price elasticities to be smaller in absolute terms than -0.3 and she finds the average income elasticity to be less than 0.4 in the short run and larger, but not above one, in the long run. Similar conclusions to Dahl's have been made in more recent surveys, most noteworthy is perhaps the meta-analysis of residential electricity use by Espey and Espey (2004). In their analysis of 36 studies, covering the years 1947 to 1997, they report short-run and long-run average price elasticities of -0.35 and -0.85 respectively. The estimated average income elasticities are 0.28 and 0.97. Kriström (2008) concludes, after performing a review over the existing literature, that price elasticities for residential energy demand averages at -0.3 in the short run and -0.7 in the long run. Estimated price elasticities can be seen to vary across energy carriers, study designs, and regions.

Dubin and McFadden (1984) conducted the first energy demand study that rigorously took into account both a discrete choice in buying certain durable goods (appliances and equipment), and a continuous choice, in the level of energy consumed (e.g. electricity). They concluded that consumers choose what durable good to buy simultaneously with choosing how much of the good's services to consume. Hence, the characteristics of the durable good (i.e. the capital stock) should be endogenous in the energy demand function. In this classic study on residential energy demand, the authors looked specifically at gas and electricity consumption and found price elasticities that range from -0.31 to -0.11 and income elasticities barely greater than zero.

No previous study has exclusively looked at European total residential energy demand or residential electricity demand using aggregated data. However, macro studies that include European countries exist and are summarized in Table 2. Haas and Schipper (1998), who use a standard GMM approach, and Liu (2004), who employs a GMM estimator, both focus on total energy demand in the OECD countries. Both find rather low price elasticities (in absolute terms), around -0.1 for the short run and -0.2 for the long run; they vary however depending on time period and energy carrier. The income elasticities found are on the other hand relatively large, with short-run income elasticities of around 0.3 and long-run income elasticities that are approximately double the size. Lee and Lee (2010) use a panel cointegration approach on a dataset covering 25 OECD countries over the period 1978 to 2004 and examine both total energy demand and electricity demand. Price elasticities are found to be -0.19 for total energy demand and -0.01 for electricity demand. Income elasticities are estimated at 0.52 for total demand and 1.08 for electricity demand.

Krishnamurthy and Kriström (2015) use cross-sectional household survey data from 2011 from eleven selected OECD countries on electricity demand. They find rather strong differences across the considered countries; price elasticities are found to range from about -0.3 (the Netherlands) to -1.5 (Australia). They estimate the average income elasticity to 0.1. Narayan, Smyth, and Prasad (2007) use an FE estimator for the G7 countries over several decades and find the long-run residential price elasticity of demand for electricity to be -1.5 and the long-run income elasticity to be 0.5. One study, by Asche et al. (2008), use aggregated panel data from 12 European countries to examine the residential demand for natural gas. A dynamic FE estimator is used and price elasticities are estimated to -0.24 for the short run and -1.54 for the long run and income elasticities to 0.33 for the short run and 2.09 for the long run.

Table 2: Previous macro studies that include European countries

Authors	**Empirical method**	**Subject**	**Demand**	**Period**	**Income elasticity**	**Price elasticity**
Asche et al. (2008)	Panel model	12 EU countries	Gas	1978-2002	Short run: 0.33; Long run: 2.09	Short run: -0.24; Long run: -1.54
Haas and Schipper (1998)	Panel model	10 OECD countries	Total	1970-1993	0.21 to 1.22	-0.51 to -0.12
Krishnamurthy and Kriström (2015)	Cross-section model	11 OECD countries	Electricity	2011	0.1	-1.5 to -0.3
Lee and Lee (2010)	Panel model	25 OECD countries	Total and electricity	1978-2004	Total demand: 0.52; Electricity: 1.08	Total demand: -0.19; Electricity: -0.01
Liu (2004)	Dynamic panel model	23 OECD countries	Total	1978-1999	Short run: 0.08 to 0.15; Long run: -0.26 to 4.20	Short run: -0.17 to 0.16; Long run: -0.52 to 0.59
Narayan et al. (2007)	Panel model	G7 countries	Total	1978-2003	0.5	-1.5
Ó Broin et al. (2015a)	Dynamic time series	4 EU countries	Space heating	1970-2005		-0.25
Ó Broin et al. (2015b)	Panel model	14 EU countries	Space heating	1990-2010		-0.16
Pindyck (1979)	Cross-section model	OECD	Total	1959-1973	0.7 to 0.8	-1.25 to -1.0
Prosser (1985)	Time-series model	OECD	Total	1960-1982	1.02	Short-run: -0.2 to -0.40
Saussay et al. (2012)	Panel model	7 EU countries	Space heating	1990-2008	0.10	-0.16

Most micro studies on the subject focus on electricity demand. Recent studies using microdata from European households generally find small income elasticities. For example, Leth-Petersen (2002) (Danish data), Damsgaard (2003) (Swedish data), Filippini (2011) (Swiss data), and Schulte and Heindl (2017) (German data), all report short-run energy expenditure elasticities in the range of 0.1 to 0.7 for residential energy demand. Those micro studies focusing on total residential demand are Baker and Blundell (1991) (UK data), Nesbakken (1999) (Norwegian data), and Rehdanz (2007) (German data) display similar results; i.e. income elasticities are found to be in a similar range as those found for electricity demand. The price elasticities from these studies range from -0.2 to -0.9 while the studies that exclusively focus on electricity demand find considerably lower price elasticities that average around -0.2.

The heterogeneous results regarding both price and income effects found in the literature can have several explanations. Price and income elasticities typically vary with data type, estimation technique, and the concept of income used can be of importance. Dahl (1993), for instance, finds that studies using aggregated data generally find smaller elasticities than studies using disaggregated data. She argues that the larger elasticities found in studies using disaggregated data could be since they captured demographic changes more efficiently. Espey and Espey (2004) in their turn find from their meta-analysis that dynamic models tend to produce smaller elasticities compared to non-dynamic models. The authors speculate that this might be due to researchers' failure to account for possible endogeneity bias from the lagged endogenous variable. Kriström (2008) adds, that in micro-econometric studies, the measurement of income is exposed to households' reluctance of reporting their true income. Finally, it should be stressed that price and income elasticities are not necessarily homogenous over groups. For example, income responses are likely to be lower in the top of the income distribution (Baker & Blundell, 1991), they have been found to be lower for newly established households (Halvorsen & Larsen, 2001), and they vary with socio-economic factors in general (Kriström, 2008).

The present study complements the existing literature through the modelling of both total energy demand and electricity demand in the European residential sector. Using more recent data, similar estimation techniques to a number of existing studies are used, namely FE estimator (e.g. Haas & Schipper, 1998; Narayan et al., 2007; Asche et al., 2008) and GMM estimator (e.g. Liu, 2004; Alberini & Filippini, 2011) provides easily comparable results. This study, in addition, applies the more recent LSDVC estimator which has (as far as the author knows) only been applied twice before for energy demand analysis, by Hung and Huang (2015) in a Taiwanese urban area and by Filippini (2011) in a micro setting in Switzerland. In addition to this contribution, this study is the first ever to use a dynamic panel data approach to examine residential space heating demand. Below follows an overview of the limited literature that examines European space heating demand.

2.2 Energy Demand for Space Heating

The demand for space heating accounts for a large part of total energy demand, about two-thirds in the EU according to Odyssee data (Enerdata, 2018b). In addition, the behavior of space heating demand is likely to differ from electricity demand for appliances (Brounen et al., 2012). Yet, only a handful of studies have been conducted which focus on space heating demand (likely because of the scarcity of data). Hence, a separate analysis is warranted.

Three micro studies have empirically estimated residential energy demand for space heating; all are conducted in Germany. Rehdanz (2007) examines oil and gas use for space heating using survey data from 1998 and 2003. The author finds a price elasticity of approximately -1.68 for oil and -0.44 for gas. Meier and Rehdanz (2010) also use time series data on the household level from 1991 to 2005. Over this period, they find a price elasticity for gas demand for space heating of -0.27. Schulte and Heindl (2017) estimate the own price elasticity for space heating to -0.50 and the expenditure elasticity to 0.41 in Germany for the period 1993 to 2008.

Likewise, only three macro studies empirically estimate energy for space heating demand, all of which have a European focus. Saussay et al. (2012) employ a random effects estimator on a panel dataset that covers the period 1990 to 2008 for seven countries; namely Austria, Denmark, Finland, France, Germany, Poland, and the UK. The authors identify the price elasticity under the period to be -0.16 and the income elasticity to 0.10. Ó Broin et al. (2015b) estimates the average long-run price elasticity to -0.25 by employing separate autoregressive distributed lag models on the four European countries France, Italy, Sweden, and the UK. The study covers an unusually long time-span for these kinds of studies and utilizes data that stretches from 1970 to 2005. Ó Broin et al. (2015a) instead examines a larger number of countries (EU-15 except for

Luxemburg) but with a shorter time-span: 1990 to 2010. The authors employ a static FE model and find results that indicate a long-run price elasticity of -0.16. No statistically significant income effect was found.

When estimating these elasticities, neither Saussay et al. (2012) nor Ó Broin et al. (2015a) take into account the dynamic nature of energy demand. Ó Broin et al. (2015b) on the other hand, use dynamic autoregressive models but do not have the possibility to control for unobserved heterogeneity between countries. Neither does Saussay et al. (2012). The present study takes into account both of these factors for the estimation of demand elasticities and, in addition, it takes into account the endogeneity of the lagged variable when doing so. Furthermore, this study uses more recent data that stretches up to 2015.

2.3 Empirical Studies on Energy Efficiency Measures

In addition to the examination of the standard demand determinants price and income, this study examines the impact of energy efficiency policies and measures implemented in the selected countries in the last three decades. There exists only a relatively recent literature that analyzes the impact of such measures on residential energy demand. Bigano et al. (2011) is the first study that investigates the influence on adopted energy efficiency measures on demand. The authors use energy intensity (units of energy per unit of GDP) as a proxy for energy efficiency and regress it on several factors such as price, income, and dummy variables representing the presence of energy policy measures promoting energy efficiency. The authors conclude that energy efficiency in the EU residential sector has improved, in particular, by the application of mandatory building standards.

Filippini and Hunt (2011, 2012) analyze the effect of energy efficiency policies through the analysis of the Underlying Energy Demand Trend (UEDT) which aims to capture the combined impact of both autonomous technical progress and policy. The authors further introduce a stochastic frontier approach that serves as a measure of energy efficiency. Following Filippini and Hunt (2011, 2012), Saussay et al. (2012) and Filippini et al. (2014) both employ similar stochastic frontier approaches. Saussay et al. (2012) focus exclusively on building standards in the residential sector and represent the policies through an index that increases by one for every year a policy is in force. They find a significant decreasing effect on demand from the building standard index in seven European countries. Filippini et al. (2014) instead investigate total residential demand (in EU-27) by using a series of dummy variables representing building standards, financial measures, standards aimed at appliances, and informational measures. The authors conclude that financial instruments have had the most substantial impact on demand followed by building standards. The most recent study by Ó Broin et al. (2015a) in turn use a policy index approach based on previous evaluations of the individual policies in EU-15 except for Luxembourg. They argue that regulatory policies, including building standards, have a strong impact (and that this impact is consistent over time). In addition, some evidence of financial policies to influence demand is found. A summarized comparison of these studies and the present study can be found in Table 3.

The studies cited in Table 3 can be seen to represent a discourse initiated by Bigano et al. (2011) in which panel data are used to examine the extent to which the energy efficiency-focused policies introduced across the EU have

Table 3: Methodologies used in this and previous studies

	This study	**Ó Broin et al. (2015a)**	**Filippini et al. (2014)**	**Saussay et al. (2012)**	**Bigano et al. (2011)**
Temporal scope	1990-2015	1990–2010	1996–2009	1990–2008	1980–2006
Spatial scope	Six EU countries: France, Germany, Italy, Spain, Sweden, and the UK	EU-15 except Luxembourg	EU-27 except Malta	Seven EU countries: Austria, Denmark, Finland, France, Germany, Poland and the UK	EU-15 and Norway
Panel structure	Balanced	Balanced	Unbalanced	Unbalanced	Unbalanced
Panel approach	Fixed Effects	Fixed Effects	Fixed and random effects separately	Random effects	Fixed effects
Dependent variable	Total Consumption (TWh/year) of residential sector space heating energy demand from five energy carriers: electricity, natural gas, oil, coal and district heating	Unit Consumption (kWh/m2/year) of residential sector space heating energy demand from five energy carriers: electricity, natural gas, oil, coal and district heating	Total energy demand in residential sector	Sum of residential sector space heating energy demand from three energy carriers: electricity, natural gas and oil	Unit consumption for total energy demand in residential sector
Price variable	WAP for heat from five energy carriers: coal, district heating, electricity, natural gas and oil.	WAP for heat from five energy carriers: coal, district heating, electricity, natural gas and oil.	Index of household energy prices	WAP of market prices for three energy carriers: electricity, natural gas and oil.	Electricity prices
Policy data source	MURE Policy Database	MURE Policy Database	MURE Policy Database	IEA BEEP	MURE Policy Database
Policy parameterization	Separate dummy variables for cases of 1–2 or >2 policies in a particular category that are in force. In addition, U-values and building stock growth rates are used	Index that increases by 20, 10 or 1 every time a High-, Medium-, or Low-impact policy is introduced respectively.	Separate dummy variables for cases of 1–2 or >2 policies in a particular category that are in force.	Index that increases by 1 for every year a policy is in force.	Dummy variable for each year at least one policy in a particular category is in force.
Inclusion of policy variables in model	Variable in three different dynamic models	Variable in panel OLS	Stochastic frontier approach	Stochastic frontier approach	Variable in panel OLS
Lagged effects of policy variables	One year lag	Up to 7 years	None	Implicit via annually increasing policy index	Up to 2 years
Lagged endogenous variable	Yes	No	No	No	No
Policy categories modelled	Six: (i,ii) building standards; (iii,iv) financial; (v) appliances; and (vi) information	Four: (i) all; (ii) financial; (iii) informative; and (iv) regulatory	Six: (i,ii) building standards; (iii,iv) financial; (v) appliances; and (vi) information	One: building standards	Twelve categories

Source: Updated and modified table from Ó Broin et al. (2015a).

succeeded in reducing residential energy demand. The papers in question differ from more common residential sector models in the literature (e.g. Haas & Schipper, 1998; Alberini & Filippini, 2011), in that they explicitly include variables that represents energy efficiency policies.

While all four previous papers provide valuable insights into estimation methods and the impact of efficiency policies, the methods used for quantifying the actual energy efficiency policies in place are somewhat rudimentary. Bigano et al. (2011) do not account for the number of policies in place, but only if any policy is in place or not, while Saussay et al. (2012) simply count the number of present policies. Indeed, Bigano et al. (2011, p. 39) state in their conclusion that "it would have been [more] interesting to ... use continuous instead of binary policy variables" while Saussay et al. (2012, p. 9) declare that "the parameterization we chose for the building energy codes is admittedly fairly simple, and would call for further improvements". Filippini et al. (2014), in turn, fail to account for the fact that most regulatory standards apply to only new buildings. Ó Broin et al. (2015a) construct an index based on semi-quantitative evaluations of the policies and is to some extent subjectively determined.

The present study contributes to the literature both in terms of the representation and estimation of the policy impacts. The representation of implemented policies in this study includes previous approaches such as the UEDT (Filippini & Hunt, 2011, 2012) and the dummy variable approach suggested by Filippini et al. (2014). It also includes novel approaches by the use of minimum insulation levels (U-values) and an improved dummy approach that accounts for the fact that building standards generally apply to new buildings. This thesis also applies more sophisticated econometric approaches as described in the empirical strategy section, allowing for a dynamic specification of the demand equation.

3 Institutional Background

One of the aims of this study is to evaluate the impact from different categories of energy efficiency policy measures on residential energy demand. A significant share of the national measures on energy efficiency originates from EU directives, hence a description of the development in this area provides some context and serves as background for this thesis. The remainder of this section gives an overview of the development, with a focus on the residential sector, of EU energy policy objectives and adopted energy efficiency measures.

Since the oil shocks in the 1970s, promotion of efficient use of energy has received a lot of attention and has been an important policy objective of the EU member states. In later years, from the 1980s and onwards, as a result of both structural change and policy, member states have managed to decouple economic growth from energy consumption (IEA, 2009b). In the 1990s however, the decoupling seems to have stalled. As reported by the European Commission (EC, 1998), the rate of which the energy intensity declined in the EU-15 was higher before 1990 than afterwards. Hence, despite commitments from the EU to promote energy savings and the introduction of various instruments and programs, recent energy intensity reductions can be seen as unsatisfactory. The European Commission (EC, 2000) attributes the development to decreasing energy prices and the relatively low prioritization given to energy savings and demand-side management by member states. The European Commission further identified several market failures and barriers to investments in energy-efficiency such as institutional, financial, and legal barriers and lack of information.

The energy efficiency policies in the late 1990s and the following decade were to a large extent established as a response to rising energy security issues and the Kyoto protocol. A target to reduce energy intensity of final consumption was set by the Council of the EU (1998); the energy intensity of final consumption should be reduced by a further one percentage point per year on average (relative to the trend) for the EU to reach its full energy savings potential by 2010. Through the Action Plan to Improve Energy Efficiency in the European Community (EC, 2000), policies and measures for realization of the energy savings potential and removal of the market barriers were implemented. However, as reported in the Green Paper on Energy Efficiency 'Doing More with Less' (EC, 2005), these efforts again proved to be insufficient in terms of reaching their goals, and a new round of energy efficiency debates commenced, this time in the light of increasing energy prices and environmental concerns. The Green Paper estimated that it should be cost-effective for the EU to reduce energy consumption by 20 percent compared to the projections for 2020. The action plan that followed (EC, 2006), suggested a large number of cost-effective measures to realize the saving potential.

In accordance with an EU directive on energy end-use efficiency and energy services that was adopted in 2006 (Directive 2006/32/EC), the EU member states were to achieve a nine percent saving in final energy consumption from 2008 to 2016. It further required member states to formulate National Energy Efficiency Action Plans (NEEAPs), putting forward various sector-specific, cross-sectoral, and horizontal measures which would allow reaching the planned savings. It should be noted here that the directive's target was only indicative and non-mandatory, and it did not aim to realize the full potential for energy savings, but it was merely a first step towards reaching the 20 percent target. The Energy Efficiency Plan 2011, therefore, proposed additional measures to close this gap (EC, 2011). It was in its turn accompanied by a new energy-efficiency directive (Directive 2012/27/EU) which became effective in 2012.

The residential sector accounts for approximately 25 percent of the final energy consumption in the EU (Enerdata, 2018b). The sector has an estimated 27 percent potential for cost-effective energy savings (EC, 2006). Huge energy saving opportunities lie in retrofitted roofs and wall insulation of buildings as well as improved energy-using equipment (Castleton, Stovin, Beck, & Davison, 2010). Despite this potential, energy savings in the sector have arguably progressed at a rather slow pace. Odyssee data show that the reduction in the EU's total final energy consumption between 1996 and 2007 was 13 percent in total, while the residential sector reduced energy use by only eight percent during the same period. There is furthermore a considerable variation in achieved progress in the sector between countries; half of the member states realized less than the one percent annual savings requested in the Energy Efficiency and Energy Service Directive (Directive 2006/32/EC).

Various hurdles such as transaction costs, information asymmetries, adverse incentives for owners and tenants, lack of investment funds, and other institutional obstacles, hinder implementation of cost-effective energy savings in the residential sector. In an effort to overcome some of these barriers, member states have introduced several energy policy instruments to promote energy efficiency.

Table 4 presents an overview of adopted measures in the six countries of focus in this study. It reveals a predominant use of legislative measures (i.e., energy performance standards) and financial incentives (e.g., grants and subsidies), and low use of informative measures such as labelling and educational campaigns. The number of implemented energy-efficiency measures and the policy mix, of course, vary across member states.

Table 4: Adopted energy-efficiency policy measures from 1974 to 2015

	Number of policy measures by measure type					
Member states	Legislative/ performance standards	Legislative/ informative-labelling	Information/ education	Financial/ fiscal	Other	**Total**
France	15	8	5	24	1	**53**
Germany	18	12	4	7	4	**45**
Italy	17	10	2	5	0	**34**
Spain	42	9	6	25	3	**85**
Sweden	4	7	4	6	2	**23**
United Kingdom	25	3	10	15	2	**55**
Total	**121**	**49**	**31**	**82**	**12**	**295**

Source: Data and classifications are from MURE Policy Database (Enerdata, 2018a).

The individual policy measures act in very different ways. Performance standards (e.g. efficiency standards of heating systems and insulation standards of buildings) generally span over a long period and get stricter over time. This is not necessarily the case for information campaigns and financial incentives, especially since they are not necessarily provided on a continuous basis (IEA, 2009a). Despite this heterogeneity, the impact of individual measures should not be evaluated in isolation, since different measures can influence each other and are often implemented together as an effort to produce an effective policy mix. A package of financial incentives can support a range of programs related to energy-efficient renovation of buildings and sustainable building construction, efficient electricity use, installation of energy-efficient heating systems, and schemes for efficient energy use for low-income households. To facilitate behavioral changes, this can furthermore be accompanied by provision of information, educational and awareness-raising campaigns, promotional and training programs, and demonstration projects.

Many of the implemented energy efficiency measures in the last couple of decades are the result of EU policy (IEA, 2009a). The EU energy efficiency policies appear to be of great importance in the residential sector since they already represent about one-third of all efficiency policies in place today at the national level. These include the directives on energy efficiency, labeling of electrical appliances, eco-design for energy using products, and the Energy Performance of Buildings Directive (EPBD) which is the EU's flagship legislation covering the reduction of the energy consumption of buildings. The first version of the EPBD (Directive 2002/91/EC), was approved in 2002 and demanded compliance through the implementation of necessary laws, regulations, and administrative provisions from all EU member states before January 2006. In particular, the EPBD mandated the introduction of minimum efficiency standards of buildings in each country as well as energy performance certification of buildings. The 2002 directive was later replaced by the so-called 'EPBD recast'

(Directive 2010/31/EU), which was put into force in June 2010. The recast broadened the focus on nearly zero-energy buildings, cost-optimal levels of minimum energy performance requirements as well as improved policies. In 2016, the European Commission further published a proposal for an additional recast called 'Clean Energy For all Europeans' (COM/2016/0765) which has yet not been implemented.

In addition to the direct measures described above, many European countries have implemented pricing measures that are likely to have an indirect effect on energy efficiency. The EU cap-and-trade program EU ETS operates in all EU member states and a number of energy taxes are present. However, only four out of the six countries included in this study have implemented a carbon tax to curb greenhouse gas emissions. Sweden has been a front-runner in launching specific carbon taxes with the implementation of an initial level already in 1990. Concerns over climate change coincided with policies in Sweden aiming to reduce income taxes and to address these two issues in combination, a series of tax shifting packages were created which have been, in the main, revenue-neutral (Andersen, 2004). Towards the close of the century, Germany (1998) and the UK (2000) followed. While the UK presented a specific climate change levy on fossil fuels, Germany increased more broadly its energy taxes as part of a so-called ecological tax reform. In France, a carbon tax went into force in 2014, while Italy and Spain have no pronounced carbon tax to this date.

As described in Section 5 in this thesis, the information included in Table 4 was used in this study to construct the variables considered in the econometric analysis that aims to reflect the choice and intensity of the energy policy instruments adopted by the countries of focus.

4 A Theoretical Model of Household Demand

A reasonable starting point for a study on residential energy demand is household production theory. According to this theory, energy is not a consumption good, as it would be considered in standard consumption theory, but an input factor to the household production process. This opens the way to a rich formulation of the demand function.[1]

Residential demand for energy is largely a demand derived from the demand for a warm house. It can also include the demand for hot water, cooked food, etc., and it can be specified using a basic framework of household production theory. The theory states that households purchase 'goods' on the market. These goods serve as inputs that are used in the production processes, to produce 'commodities' which appear as arguments in the household's utility function. A household combines energy (that can have its origin from different energy carriers) and capital equipment (e.g. a house and a heating system) to produce a composite energy commodity.

The Constant Elasticity of Substitution (CES) function is one of the most commonly used production functions (see e.g. Prywes, 1986; Chang, 1994) and will be used for the particular case of this study. The output of the composite energy commodity S is produced in a household through the inputs energy, E,

[1] Becker (1965), Muth (1966), and Deaton and Muellbauer (1980) present household production theory in detail. Dubin and McFadden (1984), Flaig (1990), and Alberini and Filippini (2011) have previously applied it to energy demand analysis.

and capital, K, as follows:

$$S(E,K) = (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{p}} \tag{1}$$

where

$$\rho = \frac{\varepsilon - 1}{\varepsilon}; -\infty < \rho < 1.$$

ω_E is the share parameter of energy, ω_K is share parameter of capital ($0 < \omega_E$, $0 < \omega_K$, $\omega_E + \omega_K = 1$), and ε is the absolute elasticity of substitution ($\varepsilon > 0$). ρ is then a constant parameter; E and K are complements if $\rho < 0$ while they are substitutes if $\rho > 0$ (neither if $\rho = 0$). The production function is increasing and concave in both E and K; $S_Y > 0$, $S_{YY} < 0$ for both $Y \in \{E, K\}$.

The household is furthermore assumed to have a utility function that takes the commonly used Cobb-Douglas form, with the standard properties of differentiability and curvature, that here will allow for relatively tractable solutions. Included arguments are the composite energy commodity S and a purchased composite good X that directly yields utility:

$$U(S,X) = S^\psi X^{1-\psi}. \tag{2}$$

The utility function is increasing and concave in both S and X; $U_Y > 0, U_{YY} < 0$ for both $Y \in \{S, X\}$. ψ is the share consumed of S ($0 < \psi < 1$). The household maximizes utility subject to Equation (1) and the budget constraint:

$$I - P_s S - P_x X = 0 \tag{3}$$

where I is monetary income and P_s is price of the composite energy commodity. We take other goods and services, X, as the numeraire and, therefore, its price, P_x, is henceforth normalized to unity.

Deaton and Muellbauer (1980) present the household decision as a two-stage optimization problem. In the first stage, the household behaves like a firm, with the objective of minimizing the cost of producing the composite commodity (S) and in the second stage the household maximizes utility. In the analysis in this study, a distinction is made between short-run optimization, where K is taken as fixed at $\bar{K}$, and long-run optimization, where K is fully flexible.

The text below presents the optimization problems and core results. Detailed derivations can be found in Appendix A.1 and A.2. We start out by solving the cost-minimizing problem for the long run:

$$\min_{E,K} \quad (P_E E + P_K K) \quad \text{s.t.} \quad S = (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{p}}, \tag{4}$$

where P_E is the price of the energy and P_K is the price of the capital stock. The optimization of this problem gives the following long-run (LR) input demand functions:

$$E_{LR}(P_E, P_K, S) = S\left(\omega_E + \omega_K \left(\frac{\omega_E P_K}{\omega_K P_E}\right)^{\frac{\rho}{\rho-1}}\right)^{-\frac{1}{p}}; \tag{5}$$

$$K_{LR}(P_E, P_K, S) = S\left(\omega_K + \omega_E \left(\frac{\omega_E P_K}{\omega_K P_E}\right)^{-\frac{\rho}{\rho-1}}\right)^{-\frac{1}{p}}. \tag{6}$$

The demand for energy is decreasing in energy price and increasing in price of capital; the opposite is true for the demand for capital. The household's cost function, that is, the value of the household's costs when the cost-minimizing quantities of the two inputs are used, can be written as $C = P_E E + P_K E$. In the long run, this equals the long-run price of S multiplied by the quantity (S):

$$C_{LR}(P_E, P_K, S) = P_E E_{LR}(P_E, P_K, S) + P_K K_{LR}(P_E, P_K, S) = P_S^{LR} S \quad (7)$$

where

$$P_S^{LR} \equiv \left(\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}}. \quad (8)$$

We can note that the long-run cost is increasing in the composite commodity and the long-run price P_S^{LR}. The long-run price in its turn is increasing in the individual input prices.

In the second stage of the optimization problem, the household maximizes the utility function. By using the standard Cobb-Douglas utility function, the long-run maximization problem becomes:

$$\max_{S,X} \ U = S^{\psi} X^{1-\psi} \quad \text{s.t.} \quad P_S^{LR} S + X \leq I. \quad (9)$$

The solution to the optimization problem gives the optimal long-run demand functions for commodities S and X:

$$S_{LR}^{*}(I, P_E, P_K) = \frac{\psi I}{P_S^{LR}}; \quad (10)$$

$$X_{LR}^{*}(I) = (1-\psi) I. \quad (11)$$

It can be observed that a share ψ of income is spent on commodity S and the remaining share is spent on commodity X. Space heating demand decreases with the long-run price P_S^{LR} and both demands increase with income I.

Finally, after substituting the utility maximizing demand equation for commodity S, Equation (10), into the cost minimizing input demand functions, Equations (5) and (6), the following input demand functions are found:

$$E_{LR}^{*}(I, P_E, P_K) = \frac{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{1}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}}} \psi I; \quad (12)$$

$$K_{LR}^{*}(I, P_E, P_K) = \frac{\omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{1}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}}} \psi I. \quad (13)$$

Equations (12) and (13) represent the long-run equilibrium of the household. From Equation (12) the long-run price and income elasticities are found to be:

$$\eta_{P_E}^{LR} = \frac{\partial E_{LR}^{*}}{\partial P_E} \frac{P_E}{E_{LR}^{*}} = \frac{1}{\rho - 1} \left[1 + \rho \frac{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}}} \right]; \quad (14)$$

$$\eta_I^{LR} = \frac{\partial E_{LR}^{*}}{\partial I} \frac{I}{E_{LR}^{*}} = 1. \quad (15)$$

In the long run, the income elasticity is positive and equal to 1. The price elasticity is a function of the share parameters and prices of E and K. It is negative if the goods are (weak) substitutes ($0 \leq \rho < 1$). For ρ sufficiently negative (E and K strongly complementary), it is not immediately clear whether $\eta_{P_E}^{LR}$ remains negative or turns positive.

Whether energy and capital are substitutes or complements is hard to say *ex ante*. If K and E are complements in the production, then an increase in energy price would lead to a decline in the rate of capital formation. Alternatively, if K and E are substitutes, an increase in price spur more rapid capital formation.

Several arguments can be raised both in favor of substitutability and complementarity. On the one hand, the goods may be seen as complementary since a household needs both energy and capital together to produce space heating - it is hard to produce space heating with only capital and likewise, it is difficult to produce space heating with only energy. On the other hand, in a situation where consumers demand more space heating, they may be faced with the choice between purchasing more capital equipment or more energy; hence, treating the input goods as substitutes. Thus, the matter needs to be determined empirically. The literature contains contradictory evidence on the topic. However, the meta study by Koetse, de Groot, and Florax (2008) concludes that the collective evidence point at capital-energy substitutability in the European economy. Jaccard and Bataille (2000) find weak substitutability between the goods in the residential sector.

In the short run (SR), where capital is fixed at $\bar{K}$, the production function is expressed as:

$$S = \left(\omega_E E^\rho + \omega_K \bar{K}^\rho\right)^{\frac{1}{\rho}}. \tag{16}$$

By rearranging, the short-run E can be solved as:

$$E_{SR}\left(S\right) = \left(\frac{S^\rho - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}}. \tag{17}$$

The short-run cost function then becomes:

$$C_{SR}\left(P_E, P_{\bar{K}}, S\right) = P_E E_{SR} + P_K \bar{K} = P_E \left(\frac{S^\rho - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}} + P_{\bar{K}} \bar{K}. \tag{18}$$

We can note that the short-run costs increase with the price of both energy and capital, and with the composite commodity space heating S. This is intuitive since we would expect the costs to increase if price or quantity increases.

In the second stage of the optimization problem, where the household maximizes the utility function, the short run maximization problem becomes:

$$\max_{S,X}\ U = S^\psi X^{1-\psi} \quad \text{s.t.} \quad \left(P_E \left(\frac{S^\rho - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}} + P_{\bar{K}} \bar{K}\right) S + X \leq I. \tag{19}$$

Solving the optimization problem gives:

$$0 = P_{\bar{K}} \bar{K} + P_E \left(\frac{S_{SR}^{*\rho} - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}} \left[1 + \left(\frac{1-\psi}{\psi}\right)\left(\frac{S_{SR}^{*\rho}}{S_{SR}^{*\rho} - \omega_K \bar{K}^\rho}\right)\right] - I, \tag{20}$$

which is an implicit solution for S^*_{SR} as a function of I, P_E, and $P_{\bar{K}}$. Substituting in S from Equation (16) gives the implicit solution of E^*_{SR} as a function of I, P_E, and $P_{\bar{K}}$:

$$0 = P_{\bar{K}}\bar{K} + P_E\left(\frac{1}{\psi}\right)E^*_{SR}\left(1 + (1-\psi)\left(\frac{\omega_K}{\omega_E}\right)\left(\frac{E^*_{SR}}{\bar{K}^\rho}\right)^{-\rho}\right) - I. \tag{21}$$

From this expression, by taking the total derivative, we can obtain the following short-run price and income elasticities:

$$\eta^{SR}_{P_E} = \frac{dE^*_{SR}}{dP_E}\frac{P_E}{E^*_{SR}} = -\frac{1 + (1-\psi)\left(\frac{E^*_{SR}}{\bar{K}}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)}{1 + (1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{\bar{K}}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)}; \tag{22}$$

$$\eta^{SR}_{I} = \frac{dE^*_{SR}}{dI}\frac{I}{E^*_{SR}} = \frac{\psi I}{P_E E^*_{SR}}\frac{1}{\left[1 + (1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{\bar{K}}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)\right]}. \tag{23}$$

From the short-run elasticities, it can be noted that the price elasticity is negative and the income elasticity is positive for all possible values of ρ.

The elasticities for the short and long run can be compared.[2] Starting out with the price elasticities, the inequality $\eta^{LR}_{P_E} < \eta^{SR}_{P_E}$ can be rearranged to:

$$\rho > 0. \tag{24}$$

This implies that, if E and K are substitutes, the price sensitivity is larger in the long run than in the short run. This is intuitive. In the short run K is given, and hence, the household's consumption options are only E and X. In the long run, on the other hand, households may also adjust their level of K. For substitutability between E and K, increasing K adds additional downward pressures on E from an increase in energy prices.

Regarding the income elasticities. For $\eta^{SR}_{P_E} < \eta^{LR}_{P_I}$, the long run demand sensitivity to income changes is greater in the long run since both $\eta^{LR}_{P_I}$ and $\eta^{SR}_{P_I}$ are strictly positive. By assuming that we are in the long-run equilibrium and substituting E from Equation (12) and K from Equation (13), the inequality can be expressed as:

$$\rho < \frac{\psi}{\psi - 1}. \tag{25}$$

Thus, since $0 < \psi < 1$, the right-hand side of the expression above is always negative. Hence, the inequality is only satisfied for sufficiently negative ρ. So only if the goods are sufficiently complementary do we find a larger long-run income elasticity. This is intuitive. In the long run, households may not only spend their income on E and X, but also on K. The effect from strong complementarity between E and K (where increasing K yields increasing E), more than compensates for the fact that increasing K takes some budget from E.

Since it is unclear if energy and capital are substitutes or complements, the short-run and long-run elasticities need to be determined empirically. The size of the effect needs to be identified in addition to the the sign of the effects. To examine this, a partial adjustment approach as described in Section 6 will be used.

[2] The comparisons are presented in more detail in Appendix A.3.

5 Data Description

The data used in this study represent annual observations over the period 1990 to 2015 for six European countries: France, Germany, Italy, Spain, Sweden, and the United Kingdom. The countries were chosen because of the availability of relevant data extending back to 1990, their diversity in terms of climate and housing insulation levels, and the fact that the countries listed (except for Sweden) are the five largest energy consumers in the EU. Jointly they account for more than 70 percent of total EU energy demand in the residential sector (Enerdata, 2018b). For the purpose of this study, information on standard energy demand variables and policy variables was gathered from a number of databases.

5.1 Energy Demand Variables

Time series on final residential energy consumption of five energy carriers (coal, oil, gas, district heating, and electricity)[3] was collected from the Odyssee Database (Enerdata, 2018). They include information on total energy consumption ($E_{i,t}^{tot}$), energy consumption for space heating ($E_{i,t}^{sh}$), and electricity consumption ($E_{i,t}^{el}$) in terawatt hours. The variable $E_{i,t}^{tot}$ consists of energy consumption for space heating, appliances, water heating, and cooking. The data for the other variables are from the following sources: The number of heating degree days ($HDD_{i,t}$) was retrieved from Eurostat (2018).[4] The number of permanently occupied dwellings ($DWE_{i,t}$) and the average number of people per household ($PPH_{i,t}$) were both collected from the Odyssee Database. Indoor temperatures (IT_{it}) were compiled by researcher Érika Mata at the Swedish Environmental Research Institute (IVL) using a bottom-up technical model, namely the Energy, Carbon and Cost Assessment for Building Stocks model as suggested by Mata, Kalagasidis, and Johnsson (2013).

The variable representing income ($I_{i,t}$) is the net disposable income in euro normalized to year 2005 prices[5] and was provided by the AMECO database by the European Commission (AMECO, 2018). Time series of prices for the residential sector of coal, oil, gas, and electricity were also normalized to year 2005 prices (€$_{2005}$/TWh) and were provided by the International Energy Agency (IEA, 2018). Werner (2016) supplied the time series of district heating prices which were normalized to year 2005 prices using price indices from Eurostat (2018). The time series of prices for all six energy carriers was then weighted by the corresponding time series of their usage for space heating in each country; this allowed series of weighted average prices (WAPs) of energy for residential space heating ($P_{i,t}^{sh}$) and in total for the residential sector ($P_{i,t}^{tot}$) to be constructed. Descriptive statistics of the variables are presented in Table 5.

From Figure B.1 in Appendix B, it can be seen that energy consumption for space heating is higher in countries where energy prices are low. However, after

[3]Due to the nature of the trade in biomass, prices are not available in national statistics for this commodity. Thus, energy from biomass is not included.

[4]The calculation of heating degree days (HDD) relies on the base temperature, defined as the lowest daily mean air temperature not leading to indoor heating. By the use of a general climatological approach, the base temperature was set to a constant value of 15°C in the HDD calculation. If $T_m \leq 15°C$ then HDD $= \sum_j (18°C - T_m^j)$ else HDD $= 0$ where T_m^j is the mean air temperature of day j.

[5]Household and non-profit institutions serving households (NPISH) net disposable income.

Table 5: Descriptive statistics of energy demand variables

Variable	Description	Unit	Mean	SD	Min.	Max.	Data Source
E^{tot}	Total energy consumption	TWh	344	205	70.5	776	Odyssee
E^{sh}	Space heating energy consumption	TWh	226	159	26.9	602	Odyssee
E^{el}	Electricity consumption	TWh	88.9	38.9	30.2	156	Odyssee
P^{tot}	Total WAP	€$_{2005}$/TWh	980	238	549	1,569	Odyssee/Eurostat/ Werner
P^{sh}	Space heating WAP	€$_{2005}$/TWh	784	200	398	1,268	Odyssee/Eurostat/ Werner
P^{el}	Electricity price	€$_{2005}$/TWh	1,763	429	878	3,001	Odyssee
I	Net income per capita	€$_{2005}$/TWh	15,755	2,794	9,343	21,366	AMECO
HDD	Heating degree days	°C	2,89	1,176	1,482	5,874	Eurostat
DWE	Number of dwellings	Thousands	21,140	9,919	3,962	38,131	Odyssee
PPH	Average Household size	People	2.42	0.31	2	3.28	Odyssee
IT	Average Indoor temperature	°C	21.0	0.69	20.0	22.5	IVL

controlling for unobserved heterogeneity between countries, solely the within-country variation is exploited in this study. The within-country variations are displayed in Figure 1 where the development of energy consumption for space heating, heating degree days, and energy prices for the individual countries are presented as indices. The dynamics of the variables over the period show that the development has been heterogeneous between the different countries but also that the level of energy consumption has been falling in all six countries since 2005. It can further be noted that energy consumption for space heating closely tracks HDD, with spikes for colder years. The year 2010 appears to have been an exceptionally cold year in the northern countries and indeed, increased energy consumption for space heating followed. Energy prices have risen in recent years in all countries, but at varying rates. Especially large price increases can be observed in Germany, Sweden and the UK. These are the three countries that had increasing carbon taxes during the period (also France in 2014). The substantial increase in energy consumption seen in Spain can to some extent be explained by the construction boom that took off in the country year 2000.

5.2 Quantitative Representation of Efficiency Policies

For the representation of policy measures adopted in the countries studied, two approaches are employed. The present study is the first ever energy demand study that introduces U-values, which is a measure that represents insulation levels in buildings.[6] The U-values have been compiled by researcher Érika Mata

[6]More formally, the U-value is referred to as the overall heat transfer coefficient. It describes the rate of transfer of heat (in watts) through one square meter of structure divided by the

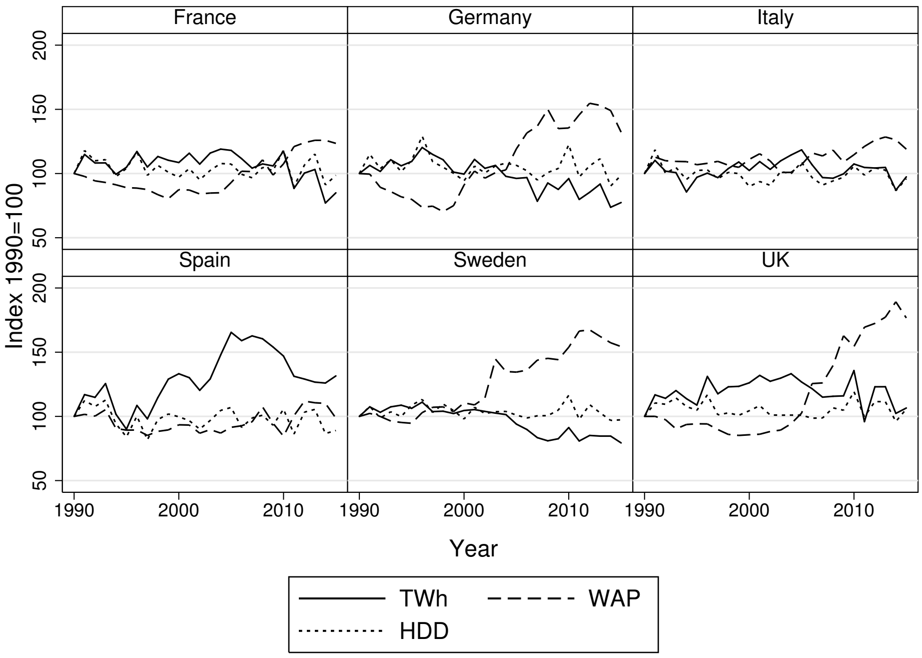

Figure 1: Indices of time series of energy consumption for space heating (TWh), weighted average energy price (WAP), and heating degree days (HDD) from 1990 to 2015. *Source: Author's own calculations. For underlying data sources see Table 5.*

at IVL from the building regulations that have been introduced since 1990. They represent the minimum allowed U-values for new building projects in the residential sector in a given country at a given year. To capture the effect of minimum insulation standards on the entire residential building stock, the variable $UX_{i,t}$ was created. The value of $UX_{i,t}$ in year t is the sum of U-values from year 1990 to year $t-1$, where each U-value is weighted by the share of the new building stock that each U-value applies to. More formally:

$$UX_{i,t} = \sum_{c=1990}^{c=t} U_{i,c-1} \left(\frac{\mathrm{m}^2_{i,c} - \mathrm{m}^2_{i,c-1}}{\mathrm{m}^2_{i,1990}} \right) \tag{26}$$

where $U_{i,c}$ is the minimum U-value in a given country, i, at a given year, $c = 1990, 1991, \ldots, t$ for $t > 1990$, and $\mathrm{m}^2_{i,c}$ is the square meter aggregate of new buildings in the residential sector in a given country at a given year.

Additionally, a dummy variable approach is employed. The dummy variables were constructed using information from MURE Policy Database (Enerdata, 2018a) as presented in Table 4.[7] The database contains, among other things, applied national measures defined in NEEAPs and EU-related measures implemented in line with the EU directives. These measures were sorted into

difference in temperature through the structure.

[7]MURE is a part of the ODYSSEE MURE project on Monitoring of Energy Demand Trends and Energy efficiency in the EU, supported under the Intelligent Energy Europe Programme of the European Commission.

three different policy groups which correspond to the most frequently used measure types, namely i) energy performance standards, ii) financial incentives, and iii) informative measures. Energy performance standards were furthermore broken into categories corresponding to standards related to buildings and heating systems, and standards related to electrical appliances and other measures.

Since different measures are often not comparable in terms of scope, impact, and required funding, there is no perfect approach for quantifying them. To reflect both the presence of a certain measure as well as the number of measures, the approach created by Filippini et al. (2014) is followed. Several dummy variables were created and are presented in Table 6.

The variable $BH1_{i,t}$ is equal to one if at least two energy performance standards related to buildings or heating systems were in place in a given country and a given year, zero otherwise. Similarly, $BH2_{i,t}$ is equal to one if three or more such performance standards were in place. $APP_{i,t}$ denotes whether at least one measure related to performance standards of electrical appliances was in place in a given country in a given year.

Furthermore, $FIN1_{i,t}$ denotes whether a given country in a given year has implemented at least two financial incentives to promote energy efficiency investments (e.g., subsidies, grants, and loans with reduced interest rate), while $FIN2_{i,t}$ indicates whether three or more such policies were in place. The threshold of two policies to separate two dummy variables in the case of both financial incentives and building and heating performance standards corresponds to the median value of the number of measures in place in a country in a given year.

Table 6: Descriptive statistics of policy variables

Variable	Description	Mean	SD	Min.	Max.	Data Source
UX	U-values weighted by the building stock composition	0.12	0.25	0	0.81	IVL/ Odyssee
$BH1$	1 if 1 or 2 building performance standards are in place; 0 otherwise	0.32	0.47	0	1	MURE
$BH2$	1 if >2 building performance standards are in place; 0 otherwise	0.24	0.43	0	1	MURE
APP	1 if any informational measure are in place; 0 otherwise	0.14	0.35	0	1	MURE
$FIN1$	1 if 1 or 2 financial instruments are in place; 0 otherwise	0.27	0.45	0	1	MURE
$FIN2$	1 if >2 building regulation are in place; 0 otherwise	0.18	0.38	0	1	MURE
$INFO$	1 if any appliances performance standards are in place; 0 otherwise	0.13	0.33	0	1	MURE
BHX	Building standards weighted by the building stock composition	0.11	0.24	0	0.78	MURE/ Odyssee

The last group of policies is represented by the variable $INFO_{i,t}$ which denotes whether at least one informative measure was in place in a given country at a given year. Informative measures include mandatory labeling of buildings, advice network for citizens, and information campaigns by specialized agencies. The decision to keep only one informative dummy is based on the low variation observed in the second informative dummy, causing serial correlation. The same decision was made for the variable $APP_{i,t}$ that represents performance standards for electrical appliances.[8]

The approach is arguably quite simplistic because, as mentioned above, the policy measures are heterogeneous in scope and stringency. Hence, by using the count of measures introduced for each group can be an imprecise way to go about it. However, given the construction of the variables, the approach gives some weight both to the presence of policy and to the number of policies.

The representation of the standards related to buildings and heating systems from the dummy approach described above can be argued to be somewhat unsatisfactory since most of these standards apply only to new buildings. Therefore, the parameterization suggested by Filippini et al. (2014) is further developed in this study. The variable $BHX_{i,t}$ is introduced and represents the standards related to buildings and heating systems. It was constructed in a similar way as $UX_{i,t}$ by the weighting of a policy variable with the share of the building stock it applies to. It represents the accumulated growth rate of the building stock in square meters since the first policy was introduced. This was then repeated for the second policy measure, the third, and so on, and the series were added together. Formally:

$$BHX_{i,t} = \sum_{c=1990}^{c=t} BH_{i,c-1} \left(\frac{\mathrm{m}^2_{i,c} - \mathrm{m}^2_{i,c-1}}{\mathrm{m}^2_{i,1990}} \right) \tag{27}$$

where $BH_{i,c}$ is a count variable equal to the number of performance standards related to buildings or heating systems in place in a given country at a given year. Through this composition, the building standards get weighted by the share of the building stock for which they apply to.[9]

6 Empirical Strategy

6.1 Model Specification

To model demand by using one model and estimate short-run and long-run elasticities of energy demand, the equation to be estimated takes the form of an autoregressive distributed lag (ARDL) model. This kind of specification is commonly used in previous energy demand literature. Dahl (1993), who performs a comprehensive review of energy demand studies, describes lagged endogenous models as the most ubiquitous approach for separating short-run and long-run effects. A general ARDL model will have the form:[10]

$$y_t = \beta_0 + \sum_{g=1}^{G} \gamma_g y_{t-g} + \sum_{h=0}^{H} \beta'_{k,h} x_{k,t-h} + \upsilon_t \tag{28}$$

where y_t is the dependent variable, γ_g, $g = 1, 2, \ldots, G$, are coefficients of autoregressive lagged values of the dependent variable, $x_{k,t-h}$, $h = 0, 1, \ldots, H$,

[8] Filippini et al. (2014) similarly use only one APP and one INFO variable based on related concerns.

[9] Another deviation from Filippini et al. (2014) is that taxation policies were not included in the variable representing financial measures. This modification was made since taxes are already represented in the price variable.

[10] For expositional purposes, this subsection abstracts from the cross-sectional dimension of the data, focusing on the time dimension only.

are k-element vectors of current and distributed lagged values of regressors and $\beta_{k,h}$ is a column vector with k coefficients. β_0 is the constant and υ_t is the error term. The way dynamic adaptation is modeled depends on the lag structure assumed. In the case of this study, the ARDL (1,0) model is used, commonly referred to as the partial adjustment model.

The separation of the short-run and the long-run are of importance for the analysis of energy demand. Households are not expected to change their consumption levels immediately after a change in demand determinants such as price and income. This can be due to several reasons. As stated in the theory in Section 4, in the short run, the capital stock is fixed; people may be 'locked' to their heating system with limited possibilities to escape from, for instance, price increases. Additionally, it may take some time for households to adjust their consumption habits. Technological reasons also account for the dynamic nature. For these reasons, partial adjustment responses can be expected from the households and are in this study modeled accordingly. The partial adjustment model for energy demand reads as follows:

$$E_t^* = \alpha_0 + \alpha_1 P_t + \alpha_2 I_t + x_t' \alpha + \epsilon_t \tag{29}$$

where E_t^* is desired demand of energy (space heating, total, or electricity) at time t. P_t is the price of energy and I_t is the per capita income at time t. Denoted x_t' is the $\{(k-3) \times 1\}$ vector of additional explanatory variables representing geographical and household characteristics (HDD, DWE, PPH, and IT) that may influence demand. The vector also includes a time trend. For the policy analysis, the policy variables listed in Table 6 are included in the vector. k is the total number of regressors. ϵ_t is an error term assumed to be identically and independently distributed with zero mean and constant variance, i.e. $\epsilon_t \sim IDD\left(0, \sigma_\epsilon^2\right)$. $\alpha_0, \alpha_1, \ldots, \alpha_k$ are model parameters.

The partial adjustment model is in line with the general ARDL model in Equation (28) and can also be derived as an approximation of the theoretical model in Section 4 (see Appendix A.4 for details). For the purpose of this study, all continuous variables are log transformed.

E_t^* is here the *desired* demand of energy which is unobservable. Desired demand is the demand that consumers would demand if they would not be stuck with their current capital stock for the reasons described above. This is to compare with *actual* demand which is equal to the level of energy that is actually being consumed. Desired demand and actual demand is equal to each other only in the long run when capital is flexible. The variable that will be used in this study is the actual demand, E_t. The relationship between desired demand and actual demand is the following:

$$E_t - E_{t-1} = \theta \left(E_t^* - E_{t-1}\right) \tag{30}$$

where $E_{t-1}$is the one-time period lag of actual demand and θ is a coefficient of adjustment that takes a value between zero and one; $\theta \in (0, 1)$. The coefficient of adjustment can be seen to reflect the speed of adjustment towards desired demand. An adjustment speed close to zero indicates a slow adjustment speed, where it takes much time for the consumers to adjust their capital stock to reach desired demand. An adjustment speed close to one indicates a fast adjustment speed, where consumers easily adapt their capital stock to reach desired demand.

Inserting the expression for E_t^* from Equation (30) into Equation (29) and rearranging yields:

$$E_t = \beta_0 + \gamma E_{t-1} + \beta_1 P_t + \beta_2 I_t + x_t' \beta + u_t \tag{31}$$

where the coefficient parameters are related to the ones in Equation (29) in the following way: $\beta = \theta\alpha$ and $\gamma = 1 - \theta$. The error term is now given by $u_t = \theta\epsilon_t$.

From Equation (31) the short-run effects of a price change can be obtained as: for the current period $\partial y_t / \partial P_t = \beta_1$, for one period after $\partial y_{t+1} / \partial P_t = \gamma\beta_1$, for two periods after $\partial y_{t+2} / \partial P_t = \gamma^2 \beta_1$, and so on. Therefore, the long-run effect of a price change, which is then the sum of all the short-run effects for each period, can be expressed as:

$$\beta_1 + \gamma\beta_1 + \gamma^2\beta_1 + \ldots = \beta_1 / (1 - \gamma). \tag{32}$$

Since all continuous variables in Equation (31) are expressed in logarithmic form, the short-run effect β_1 and the long-run effect $\beta_1 / (1 - \gamma)$ are the short-run and long-run price elasticities. These correspond to the price elasticities $\eta_{P_E}^{SR}$ and $\eta_{P_E}^{LR}$ as denoted in the theoretical framework in Section 4. Naturally, the same logic applies to income I_t; taking β_2 instead of β_1 in Equation (32) yields the income elasticities η_I^{SR} and η_I^{LR}.

6.2 Estimation Methods

The Fixed Effects (FE), Generalized Method of Moments (GMM), and Least Squares Dummy Variable Corrected (LSDVC) estimators are employed to estimate the dynamic demand. The estimation methods are applied on a macro panel dataset, where N cross-sectional units are observed over T time periods. This provides a solution to accommodating the joint occurrence of dynamics and unobserved country heterogeneity in energy demand. Since panel data is used, Equation (31) is rewritten with two dimensions as follows:

$$E_{i,t} = \beta_0 + \gamma E_{i,t-1} + \beta_1 P_{i,t} + \beta_2 I_{i,t} + x_{i,t}' \beta + u_{i,t} \tag{33}$$

where the subscript i, $i = 1, 2, \ldots, N$, represents the country. Assuming systematic variation across countries but not across time, the error term will have the structure of a one-way error component in the following way: $u_{i,t} = \mu_i + \nu_{i,t}$, where μ_i represents the unobserved country-specific effects and $\nu_{i,t}$ is the genuine error term. The error terms are assumed to be independent of each other and among themselves; $\mu_i \sim IDD\left(0, \sigma_\mu^2\right)$ and $\nu_i \sim IDD\left(0, \sigma_\nu^2\right)$. The coefficients can be directly interpreted as demand elasticities for variables in logarithmic form.

Since $E_{i,t}$ is a function of μ_i it follows that also $E_{i,t-1}$ is a function of μ_i. Thus, the regressor $E_{i,t-1}$ is correlated with the error term, which makes an FE (sometimes called Least Square Dummy Variable; LSDV) estimator biased and inconsistent for a finite T; this is shown in detail in a seminal paper by Nickell (1981). Despite this bias, the FE estimator is commonly applied by many studies in the existing energy demand literature and the estimated results can be of some reference value. The bias does not vanish as N increases, but the FE estimator becomes consistent as T grows (the endogeneity bias $\rightarrow 0$ as $T \rightarrow \infty$). The value of T is moderate in the sample used in this study ($T = 26$).

Judson and Owen (1999) performed some Monte Carlo experiments with the number of entities (N) to be 20 and the time dimension (T) to be five, ten, 20, and 30. They find that, when T = 30, the FE estimator performs just as well or better than most viable alternatives. Thus, since the endogeneity problem might not be severe, and for the reference value it serves, it is worth the effort of estimating the FE results for energy demand in this study together with the GMM and LSDVC approaches that are designed to take care of the endogeneity.[11] Robust standard errors adjusted for clustering are used for all FE estimations to deal with possible heteroscedasticity.

Since the paper by Nickell (1981), a number of consistent instrumental variable (IV) and GMM estimators have been suggested in the econometric literature as alternatives to the FE estimator. Early on, Anderson and Hsiao (1982) suggested two simple IV estimators that, after the transformation of the model in first differences, use the second lags of the dependent variable, either in levels or differenced, as instruments for the differenced one-time lagged dependent variable. Arellano and Bond (1991) instead suggested a GMM estimator for the first-differenced model, which, by relying on a greater number of internal instruments, is shown to be more efficient than Anderson and Hsiao (1982). Arellano and Bond (1991) utilize the orthogonality conditions between lagged values of the energy consumption and the genuine error term. Consistent estimates can be generated as follows. Taking the first difference of Equation (33) yields:

$$\Delta E_{i,t} = \gamma \Delta E_{i,t-1} + \beta_1 \Delta P_{i,t} + \beta_2 \Delta I_{i,t} + \Delta x'_{i,t}\beta + \Delta \nu_{i,t} \tag{34}$$

where $i = 1, 2, \ldots, N$ and $t = 3, 4, \ldots, T$. By doing this, the unobserved country effect μ_i is removed, but the lagged dependent variable is still related to the remaining unobservable: $E\left(\Delta E_{i,t-1} \Delta \nu_{i,t}\right) \neq 0$. Arellano and Bond (1991) point out that there exist qualified instrument variables that are correlated with $\Delta E_{i,t-1}$ but not with $\Delta \nu_{i,t}$, namely the second lag of the dependent variable and all feasible lags thereafter; $E_{i,1}, E_{i,2}, \ldots, E_{i,t-2}$. Robust standard errors adjusted for clustering are used for the GMM estimations in this study.

The consistent GMM estimator has been a frequent estimator in demand analysis since and is also employed in this study. However, a weakness of GMM estimators is that their properties hold only when N is large. Hence, they can be biased and imprecise in cases when the panel data only have a small number of cross-sectional units. As in most macro panels, this is also the case in this study. Consequently, an additional approach relying on bias-correction will also be used.

Bias-corrections of dynamic panel-data models with strictly exogenous regressors has recently become popular in the econometric literature. By the use of higher-order asymptotic expansion techniques, Kiviet (1995) approximates the small sample bias of the FE estimator from the expression first derived by Nickell (1981) for the inconsistency of FE for N $\rightarrow \infty$. The approximation terms, all evaluated at the unobserved true parameter values are however of no direct use for estimation. To make them operational, Kiviet (1995) proposes replacing the true parameters with the estimates from some consistent estimators. Through Monte Carlo experiments in the same paper, the author shows

[11] The Hausman test was employed to check if a Random Effects (RE) estimator would be to prefer. The null hypothesis was rejected at the five percent level for all models, indicating that the use of FE is preferred over RE for the sample.

that the resulting bias-corrected FE estimator (LSDVC) often outperforms the IV–GMM estimators in terms of bias and root mean squared error (RMSE). Further Monte Carlo evidence provided by Judson and Owen (1999) strongly supports LSDVC when N is small. Later, Kiviet (1999) modified the previous bias expression somewhat to be more accurate. After some simplification of the approximations in Kiviet (1999), Bun and Kiviet (2003) carried out Monte Carlo experiments showing that already the approximation from Kiviet (1995), was capable of accounting for more than 90 percent of the actual bias. Bruno (2005) in turn performed Monte Carlo experiments with N = 10 and T = 20 and the results show that the LSDVC outperforms all other estimators tried (among them, FE and GMM) in terms of bias and RMSE. From this scenario, the LSDVC clearly emerges as one of the preferred estimators for dynamic panel-data models with small N and strictly exogenous regressors. Hence, the LSDVC estimates are of particular focus in this study. Kiviet and Bun's (2003) paramedic bootstrap procedure to estimate the asymptotic variance-covariance matrix is employed for the LSDVC standard errors.[12]

In the section below, the FE, the one-step GMM, and the LSDVC estimators presented above are employed to estimate the determinants of residential energy demand for space heating. The paralell use of all three estimators reveal the sensitivity of the estimates to the choice of econometric estimation technique. Comparisons of estimates are also made with total energy demand and electricity demand. As for this purpose, similar model specifications are used for all three energy uses.

7 Estimation Results

The results are presented in the following two steps. First, in Section 7.1, the estimated short-run and long-run effects of price and income are discussed together with other determinants of demand. Second, in Section 7.2, the policy impacts are discussed in terms of the UEDT, minimum efficiency standards for buildings (U-values), and policy instruments. The main emphasis of the analysis is on space heating, but for comparison purposes estimations of total energy demand and electricity demand are also carried out and presented in Appendix B.[13] Finally, in Section 7.3 the results are compared to static estimation results.

7.1 Estimated Energy Demand

The estimation results of the residential space heating demand equation, using the three different estimators (FE, GMM, and LSDVC), are given in Table 7. The estimation results for total residential energy demand and residential electricity demand can be found in Table B.1 in Appendix B. Since the dependent variables and the regressors associated to the continuous variables are in

[12] The number of bootstrap repetitions selected is 1,000.

[13] In a sense, all energy consumption will turn to heat. For example, a refrigerator generates a lot of heat, as does cooking. Hence, one could argue that when examining the energy demand for residential space heating, it is a matter of choice if one wants to focus on energy consumption that is intended for space heating or total residential energy consumption. However, as energy consumption for cooking and refrigeration is not primarily intended for heating and might be unwanted (and therefore possibly ventilated away), a strict distinction between energy consumption for space heating and total energy consumption is made.

logarithmic form, the estimated coefficients are directly interpretable as short-run elasticities. The estimated coefficients all have the expected signs and are largely statistically significant in all regressions.[14]

Table 7: Estimated space heating demand

Variables	FE	GMM	LSDVC
E^{sh}_{t-1}	0.450***	0.443***	0.542***
	(0.057)	(0.050)	(0.093)
P^{sh}	−0.226***	−0.223***	−0.208***
	(0.049)	(0.042)	(0.056)
I	0.170***	0.184***	0.155***
	(0.058)	(0.053)	(0.035)
HDD	0.936***	0.940***	0.955***
	(0.080)	(0.069)	(0.087)
DWE	0.710***	0.730***	0.552***
	(0.181)	(0.159)	(0.197)
PPH	0.186	0.199	0.151
	(0.217)	(0.203)	(0.175)
IT	1.114	0.989	0.947
	(1.231)	(1.077)	(1.443)
$Trend$	−0.004*	−0.004*	−0.003
	(0.002)	(0.002)	(0.002)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The speed at which demand adapts from actual to desired demand, denoted θ in Equation (30), is found by the LSDVC estimator to be 0.46 ($= 1 - 0.54$) for space heating demand. A relatively slow adjustment speed like this one was expected. The capital stock in the residential sector is not quickly adaptable - adjusting or changing heating system, insulation levels, and appliances takes time and comes with certain costs. Interestingly, the adjustment speed for electricity is found to be even lower with an estimated value of 0.23 ($= 1 - 0.77$). The adjustment speed for total energy demand is naturally somewhere in between the two; estimated to 0.50 ($= 1 - 0.50$). These results indicate that consumers adjust their capital stock for non-electricity based space heating quicker than they adjust their electrical appliance stock.

The adjustment speeds found are furthermore in line with the findings of previous studies. It can be read from the study by Ó Broin et al. (2015b) on space heating demand that the average adjustment speed in France, Italy, and

[14]Non-stationarity tests were performed on the three consumption variables in all six countries using Augmented Dickey–Fuller tests. The null hypothesis that there is a unit root was rejected for at most one country for each consumption-level variable. Hence, non-stationary should not be a major issue for the estimators. Sargan tests from the second-step estimator have been conducted for all GMM regressions presented in this thesis. The null hypothesis of valid overidentifying restrictions was never rejected at the five percent level. Arellano-Bond tests for serial correlation in the first-differenced errors at order one and two was also performed. The null hypothesis of no serial correlation at order one was rejected for all GMM regressions and the null hypothesis was never rejected at the second order using the ten percent significance level. Indicating no model misspecification. The within R^2 measure is >0.90 and the between R^2 measure is >0.95 in all dynamic FE regressions.

Sweden is estimated to 0.55. Liu (2004) finds an average adjustment speed of 0.63 for total residential energy demand for 23 OECD countries. Similarly, Alberini and Filippini (2011) display an adjustment speed of 0.68 for the US electricity demand using an LSDVC estimator.

Table 8 presents the estimated short-run and long-run price and income elasticities calculated in accordance with Equation (32). All long-run elasticities are found to be larger in absolute terms than the short-run elasticities. The LSDVC estimator finds the short-run and long-run price elasticities for space heating to be -0.21 and -0.45 (= -0.21/0.46) respectively. These results indicate that households are expected to respond (*ceteris paribus*) to a ten percent increase in price by a 2.1 percent reduction in energy consumption for space heating in the short run. For the same price increase, in the long run, when the capital stock no longer is fixed, the energy consumption is estimated to decrease by 4.5 percent. Thus, some price sensitivity from households in their demand for space heating both in the short run and, especially, in the long run can be observed.

Electricity demand is estimated to be less price sensitive than space heating demand. The short-run price elasticity of electricity is estimated to -0.07. However, as a consequence of the slow adaptation speed in electricity demand, the long-run price sensitivity is considerably higher with an estimated elasticity of -0.30. The corresponding elasticities for total energy demand are -0.22 for the short run and -0.44 for the long run. Thus, residential energy consumers' price sensitivity in regards to all three types of energy consumption is shown to be rather modest in the short run but displays important adaptability in the long run.

Table 8: Demand elasticities

Space heating demand	FE		GMM		LSDVC	
	Short-run	Long-Run	Short-run	Long-Run	Short-run	Long-Run
Price elasticity	-0.23	-0.41	-0.22	-0.40	-0.21	-0.45
Income elasticity	0.17	0.31	0.18	0.33	0.16	0.34
Total energy demand	FE		GMM		LSDVC	
	Short-run	Long-Run	Short-run	Long-Run	Short-run	Long-Run
Price elasticity	-0.25	-0.40	-0.25	-0.38	-0.22	-0.44
Income elasticity	0.07	0.11	0.09	0.14	0.06	0.11
Electricity demand	FE		GMM		LSDVC	
	Short-run	Long-Run	Short-run	Long-Run	Short-run	Long-Run
Price elasticity	-0.07	-0.27	-0.08	-0.24	-0.07	-0.30
Income elasticity	0.06	0.22	0.07	0.23	0.06	0.25

**All results are statistically significant at the 1% level*

The estimated price elasticities in space heating demand are somewhat larger in absolute terms than the price elasticities found in previous studies on space heating demand. The short-run estimate of -0.21 suggests a higher price sensitivity than the short-run estimate of -0.16 from Ó Broin et al. (2015b). Likewise, the long-run estimate of -0.45 stands out to indicate a relatively high price sensitivity compared to what has been previously found. The previous studies on space heating demand estimate it at -0.16 (Saussay et al., 2012; Ó Broin et al., 2015a) and -0.25 (Ó Broin et al., 2015b). For total energy demand the price elasticities found in this study are somewhat smaller than the averages presented in the surveys by Dahl (1993) and Kriström (2008). For electricity demand the estimated elasticities are considerably smaller than the averages for electricity demand presented by Espey and Espey (2004).

Energy demand for space heating is also shown to be dependent on income. Similar to the estimated price elasticities, the estimated income elasticities indicate more demand sensitivity in space heating demand than in total demand and electricity demand. From the LSDVC estimator, a rise in income with ten percent is found to yield a 1.6 percent increase in energy demand for space heating in the short run. In the long run, this effect is estimated to be 3.4 percent. The estimated income elasticities for electricity demand is 0.06 in the short run and 0.25 in the long run. Total energy demand displays short-run and long-run income elasticities of 0.06 and 0.11 respectively.[15]

The estimated income elasticities for space heating demand are clearly larger than the only long-run income elasticity for European space heating previously calculated in the literature of 0.1 (Saussay et al., 2012). On the contrary, the estimated income elasticities for total demand and electricity demand are considerably smaller than the averages found in Dahl (1993) for total demand and Espey and Espey (2004) for electricity demand.

Besides price and income, among the control variables, the variable representing heating degree days (HDD) is shown to be an important determinant of space heating demand. The estimators all predict an increase in energy demand for space heating of close to one percent from a one percent increase in heating degree days. Naturally, this effect is shown to be of less importance for total energy demand where the predicted increase in consumption of a one percent increase in heating degree days is about half a percent. The same effects is estimated to just over 0.16 percent for electricity demand. It is further evident that the number of dwellings is an important determinant of demand for space heating; this is shown by the strongly significant and positive coefficients of DWE. The effect from the average household size (PPH) is not shown to have an effect on space heating demand or electricity demand, but for total demand the coefficients are positive and statistically significant at the five percent level. These coefficients, rather intuitively, indicate that more energy is being consumed in households with a larger number of members. The variable representing average indoor temperature (IT) gives coefficients with expected sign for space heating demand, however, the coefficients are not statistically significant. For total energy demand and electricity demand the indoor temperature coefficients show nonsensical results. This can be due to the low variation over time in the variable.

To examine if there is evidence of bias in elasticity estimates due to correlation between the lagged energy consumption and the error term, the coefficients from the tree estimators can be compared. We can note that the estimated elasticities from the three econometric approaches are surprisingly similar to each other. Even if the FE estimator suffers from endogeneity under the specification

[15] An alternative estimation equation was considered for the estimation of the income elasticities, leaving out the possible channels DWE and PPH. Doing this did not change the income coefficient very much. For consistency, the control variables were decided to be kept in the equation.

of dynamic panel data model, in our sample, where the number of time periods is relatively large, this bias does not seem to cause serious problems. The largest difference can be found in electricity demand where the long-run price elasticities range between -0.24 and -0.30; a 20 percent difference. Comparisons of results from the estimation techniques in the context of energy demand have been conducted once before by Alberini and Filippini (2011) in the US. They find a difference of elasticity estimates of as much as thirty percentage points (88 percent).

7.2 Influence of Energy Efficiency Measures

The time trend ($Trend$) in the demand equation represents the Underlying Energy Demand Trend (UEDT) as described by Filippini and Hunt (2011, 2012). The UEDT is said to capture the combined effect of efficiency policies and autonomous technical progress. It can be seen from Table 7 above that the estimated time-trend coefficient has the expected negative sign but is only weakly significant. For total energy demand, as presented in Table B.1 in Appendix B, the trend is statistically significant at the five percent level in the FE and GMM regressions. These coefficients indicate that the UEDT accounts for approximately 0.4 percent year on year reductions in total residential energy demand. No effect from the UEDT is found for electricity demand. The absence of an effect can be due to the rapid expansion of appliances in European households since the 1990s; the number of dishwashers per capita, for instance, doubled between 1990 and 2004 (EEA, 2018). It can also indicate that much already has been achieved in improving the efficiency of electricity use for appliances and lightning, either autonomously or via policy intervention.

To single out the effect from the development in building standards in the selected countries, first, the minimum insulation standards for new buildings in terms of U-values are introduced in the regressions. The results for space heating demand can be seen in Table 9 and the results for total energy demand and electricity demand can be found in Table B.2 in Appendix B. The coefficient for the U-value variable UX is positive and highly significant. Hence, greater stringency of building standards (lower U-values) are shown to generate significant reductions in energy consumption for space heating. This effect is similar for total energy demand and, as one would expect, considerably lower for electricity demand.

For the separation and evaluation of the different categories of policy measures, a dummy variable approach is employed. The results are presented in Table 9 for space heating demand and in Table B.3 in Appendix B for total energy demand and electricity demand. The approach is similar to the approach employed by Filippini et al. (2014); the dummy variables $FIN1$, $FIN2$, and $INFO$ are all included in the estimating equation. However, since most of the energy performance standards for buildings only apply to new buildings, this study deviates from the approach used by Filippini et al. (2014). Instead of $BH1$ and $BH2$, the variable BHX as described in Section 5 is introduced. Additionally, all policy variables are now lagged with one year. This is to account for the fact that no information is gathered of at what point during the year the different policies were introduced. Hence, it is not until the year after implementation we can be sure that all policies have gotten the opportunity to affect demand. In addition, the effect on consumption levels of some policies

Table 9: Estimated impacts of energy efficiency measures

	U-values			Policy categories		
Variables	FE	GMM	LSDVC	FE	GMM	LSDVC
E_{t-1}	0.438***	0.432***	0.530***	0.365***	0.359***	0.452***
	(0.056)	(0.050)	(0.090)	(0.058)	(0.051)	(0.085)
P	−0.188***	−0.185***	−0.173***	−0.154***	−0.154***	−0.145***
	(0.051)	(0.045)	(0.047)	(0.052)	(0.045)	(0.049)
I	0.169***	0.165***	0.154***	0.281***	0.295***	0.272***
	(0.057)	(0.052)	(0.035)	(0.064)	(0.058)	(0.042)
HDD	0.930***	0.935***	0.948***	0.929***	0.921***	0.947***
	(0.079)	(0.069)	(0.084)	(0.076)	(0.068)	(0.084)
DWE	0.700***	0.701***	0.540***	0.909***	0.967***	0.764***
	(0.178)	(0.158)	(0.191)	(0.189)	(0.173)	(0.186)
PPH	0.033	0.025	0.004	0.124	0.144	0.122
	(0.223)	(0.213)	(0.190)	(0.228)	(0.207)	(0.188)
IT	1.901	1.809	1.716	2.584*	2.696**	2.528
	(1.260)	(1.118)	(1.528)	(1.414)	(1.267)	(1.726)
$Trend$	−0.004	−0.004	−0.002	−0.006**	−0.006***	−0.004**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
UX	0.203**	0.221***	0.187***			
	(0.088)	(0.083)	(0.062)			
BHX				−0.125**	−0.122**	−0.120**
				(0.059)	(0.052)	(0.060)
$FIN1_{t-1}$				−0.043*	−0.050**	−0.048**
				(0.025)	(0.023)	(0.023)
$FIN2_{t-1}$				−0.075***	−0.075***	−0.066***
				(0.021)	(0.018)	(0.020)
$INFO_{t-1}$				0.040*	0.038*	0.043*
				(0.024)	(0.022)	(0.023)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

usually takes some time (Ó Broin et al., 2015a).[16] Furthermore, in this study, the variable representing performance standards of electrical appliances, APP, is only included in the regressions concerning total residential energy demand and electricity demand since these measures are not aimed at space heating.

The results show that several measures influence the level of energy consumption for space heating in the residential sector. Similar to the results above regarding U-values, the coefficient related to the variable that represents energy performance standards related to buildings or heating systems (BHX) is negative and statistically significant. This, together with the U-value results, indicate that building standards have an important role in reducing energy consumption for space heating. Also financial incentives appear to have important effects in reducing space heating demand. Both the financial dummies introduced in the regressions, namely $FIN1$ and $FIN2$, prove to be negative and statistically significant. The results concerning informative measures $INFO$ indicate that if there is an effect at all, it is of minor magnitude and, contrary to expectations, positive.

Total residential energy demand, as presented in Table B.3 in Appendix B shows similar findings. Both performance standards and financial measures appear to be of importance. However, for total demand, only one of the financial dummies (the one representing if there are more than two financial incentives in place) is statistically significant. None of the policy variables are statistically significant at the five percent level for electricity demand. Performance standards of electrical appliances APP do not appear to have any impact on consumption levels. The absence of impact on demand may be due to the fact that these standards, similarly to building standards, generally have an impact on energy efficiency in the longer term. This is because they mostly refer to new appliances.[17]

To perform a robustness check and for comparison purposes, the demands are in addition estimated following the exact dummy specifications from Filippini et al. (2014). The estimation results can be found in Table B.4 in Appendix B. These results echo the conclusions drawn from the results above. Financial measures are shown to be of importance together with energy performance standards related to buildings or heating systems. However, in the estimation of space heating demand, energy performance standards related to buildings or heating systems are not shown to have a statistically significant effect at the five percent level using this method. This is likely due to the fact that performance standards generally apply to new buildings and hence, this needs to be accounted for to find a statistically significant impact. Standards of electrical appliances and informative measures are still not shown to have any effect on demand using the specification from Filippini et al. (2014). Moreover, as additional robustness checks, the regressions were re-estimated with the number of energy efficiency measures replacing the respective variables representing the policy categories. Similar results were attained, although the observed significance levels were somewhat lower. In addition, to examine whether combinations of different policy types provide larger impacts compared to the measures individually, in-

[16] As a robustness check, several lag structures were tested. The same coefficients stayed significant from zero to three lags.

[17] Ideally this could be accounted for by the construction of a variable similar to BHX. However, due to lack of data on the growth of the stock of appliances, doing so was not possible.

teractions between energy efficiency dummies were also considered. However, none of the interaction terms proved to be statistically significant.

The findings regarding the impacts from energy efficiency measures are moreover in line with the results from the other previous studies. Ó Broin et al. (2015a) also find impacts from building standards and financial measures. Bigano et al. (2011) and Saussay et al. (2012) find significant impacts from building standards.

7.3 Static Comparison

As discussed in the literature review in Section 2, much of the existing literature specifies the demand equation as static and estimates demand using a static FE estimator. This approach assumes instantaneous adjustment of demand when prices or income change. Specifically, it assumes that the households can change both the rate of utilization and the stock of capital immediately. As argued above, there may be several reasons to why consumer responses rather go through a partial adjustment mechanism. Consumers are to some extent 'locked' to their current capital stock. In addition, the partial adjustment hypothesis can be strengthened by behavioral traits such as habit formation and expectations. However, to serve as comparison to estimates of previous literature, static FE results are presented in Table B.5 in Appendix B.

The price and income elasticities are estimated to -0.34 and 0.26 for space heating demand by the static estimator. The static results strengthen the dynamic findings of greater price and income sensitivity in space heating demand than in electricity demand.

Turning to the policy analysis. The true impacts of the energy efficiency measures can be argued to be partly captured by the lagged consumption variable in the dynamic estimations. Therefore, static FE regressions are also performed with the policy variables included, to serve as an additional robustness check. The estimates are presented in Table B.6 in Appendix B. It can be noted that the same coefficients are statistically significant as in the dynamic regressions. Thus, while the dynamic model does reveal a substantial difference between short and long run elasticities, the lagged consumption variable does not seem to be of great importance to the policy estimates.

8 Discussion

In the estimations presented in Section 7, price is assumed to be strictly exogenous. However, if relying on basic demand-supply theory, the price variable should be determined not only by supply, but also by the energy demanded. Thus, potentially causing simultaneity bias in the price coefficient. This is however not expected to be a major issue in the context of this study. Firstly, there are multiple other usages besides space heating for the concerned energy carriers.[18] This limits the demand effect since, for instance, a drop in demand for heating and the downward pressure on prices that follows could possibly yield a counteracting increase in demand for energy from the other sectors. Secondly, many of the energy carriers are commodities that are traded on a

[18]Residential space heating accounted for 16 percent of total final energy demand on average in the selected countries over the period 1990-2015 according to Odyssee data.

global market, hence making the energy consumption for space heating in the six countries included in this study a negligible share of total global demand. It is unlikely that the relatively small changes in demand for these countries that can be observed over time influence e.g. global oil prices in a significant way. Lastly, a significant share of the energy price is determined by local policies. Shin (1985) argues that, at the aggregate level, the potential for price to be endogenous with consumption is mitigated by the many different pricing levels and schemes at different locations. On the ground of this notion, Bernstein and Griffin (2006) and Paul et al. (2009) consider average prices as exogenous in their partial adjustment models examining electricity demand in the US. In conclusion, an effort to account for possible endogeneity in the price variable, for the setting of this study, would follow with unnecessary complexity.

Another possible problem concerning the estimated price elasticities are that, as mentioned in the institutional background of this thesis (Section 3), different measures are sometimes implemented together in an effort to produce an effective policy mix. If other policy measures are implemented in combination with an energy tax increase, the price coefficients in the standard demand regression presented in Table 7 may be downward biased (away from zero). The inclusion of policy measures in the demand equation should mitigate this problem. Indeed, when including the energy efficiency variables (see Table 9) an upward shift of six percentage points can be observed in LSDVC price coefficient. One could interpret this as being indicative of the price variable 'picking up' part of the effect of policy, when policy is not accounted for, leading to an overestimation of the price coefficient (in absolute terms). However, because of data limitations, the representation of the energy efficiency measures is imperfect and may therefore not be suitable control variables. Hence, for interpretation purposes the original estimates can be argued to be preferred. Either way, the qualitative conclusions are upheld: negative and statistically significant price elasticities with difference in size between short and long-run elasticities.

Next, the empirical findings are not fully in line with the theory. The empirically estimated price and income elasticities suggest larger price and income sensitivity in the long run than in the short run. The theory on the other hand, asserts greater price sensitivity in the long run than in the short run only for substitutability between energy and capital. While, for income, it asserts the long-run income sensitivity to be greater in the long run only for sufficient complementarity between the goods. Hence, the empirical findings conflict with the theory.

This may be due to several reasons. If not coming from issues with the empirical estimation or measurement error in the data, it suggests that there are issues with the theory. The theory may not apply to the current setting or be incomplete. It does not account for other possible factors besides price and income that may influence demand, such as weather, household size, and more. The additional factors controlled for in the empirical estimations are shown to be of great importance, in particular the proxy for weather, HDD. The theory also makes some strong assumptions, such as constant elasticity of substitution for the production function and diminishing marginal rate of substitution for the utility function. These may not hold true in practice.

The household production theory is used in parts of the energy demand literature, often only briefly mentioned or specified in general terms (see e.g., Dubin & McFadden, 1984; Flaig, 1990; Alberini & Filippini, 2011). However, the specific predictions that the theory may come with are rarely looked into and possible conflicting results might be presented without this being mentioned. In that regard, this study serves as a reminder of considering the specifics of the theoretical framework used.

A further limitation of the theoretical model is that it models adjustment to physical capital only. It is probable that behavioral change also plays an important role. Behavioral change likely goes through a similar process, where habits slowly adjust from changes in variables such as price and income. Likewise, expectations on whether changes, in for example prices, are believed to be permanent or not, can further affect the rate of adjustment in demand. The presence of behavioral patterns like these would reinforce the effect through capital found in the empirical results.

Turning to the limitations of this study. One limitation is that it covers only six European countries. Even though these countries account for over 70 percent of European energy consumption, the results could have more validity for EU policymakers if more member states could be included. A larger number of entities would also be of benefit to the empirical estimations. Such analysis would require greater availability of data. In the context of EU policy, it would be interesting to gain more knowledge also on the residential demand from eastern European countries where legacy effects might be of influence.

Moreover, within the countries that are examined in this study, local variations are likely to be present. Thus, if regional data were to be available, this would open up for more precise estimates. The estimates in this study merely represents average effects over the selected countries and, by that, disclose little about the possibly large variations that may be present within countries.

Finally, regarding the representation of the energy efficiency measures, the dummy variable approach was selected after a compromise was made between capturing the presence of policy and the count of policies. The scope and stringency of the policies are however not captured by this approach. Hence, the representation is imperfect. The representation of the building standards in terms of number of policies and U-values is furthermore a challenge. The current approach captures the effect of introduced building standards from 1990 and onwards. However, it fails to account for insulation levels of those buildings built before 1990 due to lack of data.

9 Conclusion

The promotion of energy efficiency is one of the top priorities of EU Energy Policy to, among other things, mitigate climate change, increase energy security, and enhance industry competitiveness. Due to lack of existing work, the IPCC (2014) has expressed the need of sector-related studies on the topic. The aim of this thesis was to examine the determinants of residential energy demand. The research questions to be answered were in short as follows. What are the short-run and long-run price and income elasticities of residential energy demand for space heating? How do they compare to those of total and electricity demand? Is there evidence of bias stemming from the dynamic demand specification? Lastly, which energy efficiency measures are most effective in reducing energy demand for space heating?

For the purpose of answering these questions, a dataset was built that includes information on demand determinants. The dataset covers the period from 1990 to 2015 in France, Germany, Italy, Spain, Sweden, and the UK. The thesis was conducted within the theoretical framework of household production theory. By the use of a dynamic partial adjustment approach it examined residential energy demand for space heating. Based on the characteristics of the dataset, the LSDVC estimator proposed by Kiviet (1995) was employed, as well as the standard FE estimator and the GMM estimator proposed by Arellano and Bond (1991) for comparison purposes.

The demand for energy for space heating was found to be inelastic with respect to price and income. The estimated elasticities were found to be smaller in absolute terms in the short run than in the long run. From an energy policy perspective, the results concerning price effects imply that there is some room for discouraging residential energy consumption using price increases, primarily in the long run. An increase in energy price by ten percent is estimated to yield a 4.5 percent decrease in energy consumption for space heating in the long run. Energy price increases may be attained, for example, by energy taxes on specific energy carriers. In an energy system mainly based on fossil fuels, they may also result from imposing a carbon tax to curb greenhouse gas emissions or follow from reductions in the number of emission allowances in a cap-and-trade system, such as the EU ETS. In the latter two cases, the reduction in energy consumption would presumably achieve additional reductions in carbon dioxide and conventional pollutant emissions with respect to those attained with the mere shift towards cleaner sources.

Space heating demand was furthermore shown to be more price and income elastic than electricity demand, indicating that consumers are more inclined to change their energy consumption for heating than for electrical appliances. Hence, pricing policies seem to have a greater potential for this part of demand.

The results concerning income show that energy consumption for space heating is expected to increase in particular in those countries experiencing rapid income growth. During the last two decades, the average income has increased by 24 percent in the concerned countries. If this development were to be sustained in the coming two decades, holding everything else constant, the estimates predict an increase in energy consumption of approximately eight percent. This increase is further predicted to be spurred by the growth of the building stock. However, these effects are also shown to be diminished by a milder future climate.

Moreover, in regards to the third research question, a relatively small spread in point estimates was observed between the different estimation techniques, indicating that the possible endogeneity that comes with the specification of dynamic panel models did not cause any serious problems.

Lastly, to provide some evidence of the effectiveness of energy efficiency measures implemented in the residential sector, policy measures developed both within the EU and in the respective countries were included in the models. For the representation of the policies, an improved parameterization approach was used. From this, reductions in energy consumption were linked to financial incentives and energy performance standards for buildings and heating systems. Informative measures such as labeling and educational campaigns were not shown to have a significant effect in fostering energy efficiency improvements. The measures were in addition shown to have a larger impact on space heating demand than on electricity demand. Hence, policymakers may have much to gain in energy savings by giving focus to, for example, building standards and subsidies aimed at space heating demand.

For the representation of the energy efficiency measures, this study, as well as the previous studies, had to make a compromise between capturing the effect from the presence of policy and the number of policies implemented across Europe. A challenge left for future research is to capture scope and stringency of the policies. Together with evaluations of individual policies, this could provide important additional evidence of their effect. Finally, large local variations are likely to be present within countries. Hence, the use of regional data in future studies could improve the precision of the estimates.

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A Mathematical Appendix

A.1 Long-Run Optimization

In the long run (LR), K is flexible. Thus, the minimization problem is expressed as:

$$\min_{E,K} \quad (P_E E + P_K K) \quad \text{s.t.} \quad S = (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{\rho}}. \tag{A.1}$$

The corresponding Lagrangian for the long run can then be expressed as:

$$\mathcal{L} = P_E E + P_K K + \lambda \left(S - (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{\rho}} \right). \tag{A.2}$$

From the above equation, the following first order conditions can be derived:

$$\frac{\partial \mathcal{L}}{\partial E} = P_E - \lambda \frac{1}{\rho} (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{\rho}-1} \left(\rho \omega_E E^{\rho-1}\right) = 0; \tag{A.3}$$

$$\frac{\partial \mathcal{L}}{\partial K} = P_K - \lambda \frac{1}{\rho} (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{\rho}-1} \left(\rho \omega_K K^{\rho-1}\right) = 0; \tag{A.4}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = S - (\omega_E E^\rho + \omega_K K^\rho)^{\frac{1}{\rho}} = 0, \tag{A.5}$$

where $E > 0$, $K > 0$, and $\lambda > 0$.

We solve Equation (A.3) for P_E, the Equation (A.4) for P_K, and divide P_E by P_K to obtain the condition:

$$\frac{P_E}{P_K} = \frac{\omega_E E^{\rho-1}}{\omega_K K^{\rho-1}}. \tag{A.6}$$

Solving this equation for K gives:

$$K = \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{\frac{1}{\rho-1}} E. \tag{A.7}$$

Raising both sides of Equation (A.7) above to the power ρ and substituting K^ρ into the constraint gives:

$$S = \left(\omega_E E^\rho + \omega_K \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{\frac{\rho}{\rho-1}} E^\rho \right)^{\frac{1}{\rho}} = E \left(\omega_E + \omega_K \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{\frac{\rho}{\rho-1}} \right)^{\frac{1}{\rho}}. \tag{A.8}$$

Solving for E yields:

$$E_{LR} = S \left(\omega_E + \omega_K \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{\frac{\rho}{\rho-1}} \right)^{-\frac{1}{\rho}}. \tag{A.9}$$

By substituting the right-hand side from Equation (A.9) into Equation (A.7), we find:

$$K_{LR} = S \left(\omega_K + \omega_E \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{-\frac{\rho}{\rho-1}} \right)^{-\frac{1}{\rho}}. \tag{A.10}$$

Equation (A.9) and (A.10) are the constant-output input demand functions that minimize the costs in the long run for the two inputs $E_{LR}(P_E, P_K, S)$ and $K_{LR}(P_E, P_K, S)$.

The household's cost function is $P_E E_{LR} + P_K E_{LR}$. That is, the value of the household's costs at the long-run cost-minimizing values of the two inputs:

$$C_{LR}(P_E, P_K, S) = P_E E_{LR}(P_E, P_K, S) + P_k E_{LR}(P_E, P_K, S)$$

$$= P_E S \left(\omega_E + \omega_K \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{\frac{\rho}{\rho-1}} \right)^{-\frac{1}{p}} + P_K S \left(\omega_K + \omega_E \left(\frac{\omega_E P_K}{\omega_K P_E} \right)^{-\frac{\rho}{\rho-1}} \right)^{-\frac{1}{p}}$$

$$= P_S^{LR} S \tag{A.11}$$

where

$$P_S^{LR} \equiv \left(\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}}.$$

The second step of the optimization is to maximize the household utility. Using the cost functions derived in the previous step, the maximization problems can be expressed as follows.

$$\max_{S,X} \; U = S^{\psi} X^{1-\psi} \quad \text{s.t.} \quad P_S^{LR} S + X \leq I. \tag{A.12}$$

The Lagrangian for this maximization problem can then be expressed as:

$$\mathcal{L} = S^{\psi} X^{1-\psi} + \lambda \left(I - P_S^{LR} S - X \right) \tag{A.13}$$

From the Lagrangian, the following first order conditions can be derived:

$$\frac{\partial \mathcal{L}}{\partial S} = \psi S^{\psi-1} X^{1-\psi} - \lambda P_S^{LR} = 0; \tag{A.14}$$

$$\frac{\partial \mathcal{L}}{\partial X} = (1-\psi) S^{\psi} X^{-\psi} - \lambda = 0; \tag{A.15}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = I - P_S^{LR} S - X = 0, \tag{A.16}$$

where $S > 0$, $X > 0$, and $\lambda > 0$.

Combining the first two first order conditions (A.14) and (A.15) gives:

$$S P_S^{LR} = \frac{\psi X}{(1-\psi)} \tag{A.17}$$

Substituting $S P_S^{LR}$ from Equation (A.17) into the constraint (A.16) gives:

$$X_{LR}^* = (1-\psi) I \tag{A.18}$$

By substituting X_{LR}^* into Equation (A.17) and solving for S, we find:

$$S_{LR}^* = \frac{\psi I}{P_S^{LR}} \tag{A.19}$$

Equation (A.17) and (A.18) are the optimal long-run demand functions for space heating, $S_{LR}^*(P_E, P_K, I)$, and other goods and services, $X_{LR}^*(P_E, P_K, S)$.

We then get the optimal input demand functions by substituting the utility maximizing demand functions, Equation (A.18) and Equation (A.19), into the cost minimizing input demand functions Equation (A.9) and Equation (A.10) as follows:

$$E_{LR}^{*}\left(P_E, P_K, S^{*}\left(P_E, P_K, I\right)\right) =$$
$$E_{LR}^{*}\left(I, P_E, P_K\right) = \frac{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{1}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}}} \psi I; \tag{A.20}$$

$$K_{LR}^{*}\left(P_E, P_K, S^{*}\left(P_E, P_K, I\right)\right) =$$
$$K_{LR}^{*}\left(I, P_E, P_K\right) = \frac{\omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{1}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}}} \psi I. \tag{A.21}$$

From Equation (A.20) the following long-run price and income elasticities can be derived:

$$\eta_{P_E}^{LR} = \frac{\partial E}{\partial P_E} \frac{P_E}{E} = \frac{1}{\rho - 1} \left[1 + \rho \frac{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}} P_E^{\frac{\rho}{\rho-1}} + \omega_K^{-\frac{1}{\rho-1}} P_K^{\frac{\rho}{\rho-1}}} \right]; \tag{A.22}$$

$$\eta_I^{LR} = \frac{\partial E}{\partial I} \frac{I}{E} = 1. \tag{A.23}$$

We can observe a perfect income elastic demand and a price elasticity that is negative for all levels of ρ close to zero or positive.

A.2 Short-Run Optimization

The first step of the optimization is to minimize the household costs of attaining a certain S. In the short run (SR), where capital is fixed at $\bar{K}$, E can be solved by rewriting the production function:

$$S = \left(\omega_E E^{\rho} + \omega_K \bar{K}^{\rho}\right)^{\frac{1}{\rho}} \tag{A.24}$$

to

$$E_{SR} = \left(\frac{S^{\rho} - \omega_K \bar{K}^{\rho}}{\omega_E}\right)^{\frac{1}{\rho}}. \tag{A.25}$$

We can then obtain the short-run cost function by substituting the expression for $E_{SR}(S)$:

$$C_{SR} = P_E E_{SR} + P_{\bar{K}} \bar{K} = P_E \left(\frac{S^{\rho} - \omega_K \bar{K}^{\rho}}{\omega_E}\right)^{\frac{1}{\rho}} + P_{\bar{K}} \bar{K}. \tag{A.26}$$

The short-run maximization problem can be formulated as:

$$\max_{S,X} \; U = S^{\psi} X^{1-\psi} \quad \text{s.t.} \quad \left(P_E \left(\frac{S^{\rho} - \omega_K \bar{K}^{\rho}}{\omega_E}\right)^{\frac{1}{\rho}} + P_{\bar{K}} \bar{K}\right) S + X \leq I. \tag{A.27}$$

The corresponding Lagrangian for the short run can then be expressed as:

$$\mathcal{L} = S^{\psi} X^{1-\psi} + \lambda \left(I - \left(P_E \left(\frac{S^{\rho} - \omega_K \bar{K}^{\rho}}{\omega_E}\right)^{\frac{1}{\rho}} + P_{\bar{K}} \bar{K}\right) - X\right). \tag{A.28}$$

From the Lagrangian, the following first order conditions can be derived to:

$$\frac{\partial \mathcal{L}}{\partial S} = \psi S^{\psi-1} X^{1-\psi} - \lambda P_E \left(\frac{S^\rho - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}-1} \left(\frac{S^{\rho-1}}{\omega_E}\right) = 0; \tag{A.29}$$

$$\frac{\partial \mathcal{L}}{\partial X} = (1-\psi) S^\psi X^{-\psi} - \lambda = 0; \tag{A.30}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = I - \left(P_E \left(\frac{S^\rho - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}} + P_{\bar{K}} \bar{K}\right) - X = 0, \tag{A.31}$$

where $S > 0$, $X > 0$, and $\lambda > 0$. Combining the first order conditions (A.29) and (A.30) and solving for X gives:

$$X = P_E \left(\frac{1-\psi}{\psi}\right) \left(\frac{S^\rho - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}-1} \left(\frac{S^\rho}{\omega_E}\right). \tag{A.32}$$

Substituting X from Equation (A.32) into the constraint gives solution for S as a function of I, P_E, and $P_{\bar{K}}$:

$$0 = P_{\bar{K}} \bar{K} + P_E \left(\frac{S_{SR}^{*^\rho} - \omega_K \bar{K}^\rho}{\omega_E}\right)^{\frac{1}{\rho}} \left[1 + \left(\frac{1-\psi}{\psi}\right) \left(\frac{S_{SR}^{*^\rho}}{S_{SR}^{*^\rho} - \omega_K \bar{K}^\rho}\right)\right] - I, \tag{A.33}$$

Substituting in S from Equation (A.24) gives the implicit solution of E_{SR}^* as a function of I, P_E, and $P_{\bar{K}}$:

$$0 = P_{\bar{K}} \bar{K} + P_E \left(\frac{1}{\psi}\right) E_{SR}^* \left(1 + (1-\psi) \left(\frac{\omega_K}{\omega_E}\right) \left(\frac{E_{SR}^*}{\bar{K}^\rho}\right)^{-\rho}\right) - I. \tag{A.34}$$

Taking total derivative with respect to variables $E_{SR}^{*\rho}$ and P_E gives

$$\left(\frac{1}{\psi}\right) \left[P_E \left(1 + (1-\rho)(1-\psi) \left(\frac{\omega_K K^\rho}{\omega_E E_{SR}^{*\rho}}\right)\right) dE_{SR}^* + E_{SR}^* \left(1 + (1-\psi) \left(\frac{\omega_K K^\rho}{\omega_E E_{SR}^{*\rho}}\right)\right) dP_E\right] \tag{A.35}$$

and restructuring yields the expression:

$$\frac{dE_{SR}^*}{dP_E} = -\frac{E_{SR}^* \left(1 + (1-\psi) \left(\frac{E_{SR}^*}{K}\right)^{-\rho} \left(\frac{\omega_K}{\omega_E}\right)\right)}{P_E \left(1 + (1-\rho)(1-\psi) \left(\frac{E_{SR}^*}{K}\right)^{-\rho} \left(\frac{\omega_K}{\omega_E}\right)\right)}. \tag{A.36}$$

The short-run price elasticity thus becomes:

$$\eta_{P_E}^{SR} = \frac{dE_{SR}^*}{dP_E} \frac{P_E}{E_{SR}^*} = -\frac{1 + (1-\psi) \left(\frac{E_{SR}^*}{K}\right)^{-\rho} \left(\frac{\omega_K}{\omega_E}\right)}{1 + (1-\rho)(1-\psi) \left(\frac{E_{SR}^*}{K}\right)^{-\rho} \left(\frac{\omega_K}{\omega_E}\right)}. \tag{A.37}$$

Taking total derivative of Equation (A.34) with respect to variables E_{SR}^* and I we find:

$$0 = P_E \left(\frac{1}{\psi}\right) dE_{SR}^* \left(1 + (1-\rho)(1-\psi) E_{SR}^{*-\rho} \left(\frac{\omega_K \bar{K}^\rho}{\omega_E}\right)\right) - dI; \tag{A.38}$$

$$\frac{dE^*_{SR}}{dI} = \frac{\psi}{P_E\left[1+(1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{K}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)\right]}. \tag{A.39}$$

The short-run income elasticity is then:

$$\eta_I^{SR} = \frac{dE^*_{SR}}{dI}\frac{I}{E^*_{SR}} = \frac{\psi I}{P_E E^*_{SR}}\frac{1}{\left[1+(1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{K}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)\right]}. \tag{A.40}$$

A.3 Comparison of Short and Long-Run Effects

The inequality $\eta_{P_E}^{LR} < \eta_{P_E}^{SR}$ suggests that the price elasticity is larger in absolute terms in the long run than in the short run. This implies a more price sensitivity in the long run than in the short run. From Equation (A.22) and (A.37), the inequality can be expressed as:

$$\frac{1}{\rho-1}\left[1+\rho\frac{\omega_E^{-\frac{1}{\rho-1}}P_E^{\frac{\rho}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}}P_E^{\frac{\rho}{\rho-1}}+\omega_K^{-\frac{1}{\rho-1}}P_K^{\frac{\rho}{\rho-1}}}\right] < -\frac{1+(1-\psi)\left(\frac{E^*_{SR}}{K}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)}{1+(1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{K}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)} \tag{A.41}$$

This can be arranged to:

$$0<\rho\left[\frac{\omega_E^{-\frac{1}{\rho-1}}P_E^{\frac{\rho}{\rho-1}}}{\omega_E^{-\frac{1}{\rho-1}}P_E^{\frac{\rho}{\rho-1}}+\omega_K^{-\frac{1}{\rho-1}}P_K^{\frac{\rho}{\rho-1}}}+\frac{1}{1+(1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{K}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)}\right] \tag{A.42}$$

and since $(1-\rho)$ only can take positive values and all other parameters are strictly positive and $0<\psi<1$, the expression holds for $\rho>0$ only. Thus, $\eta_{P_E}^{LR} < \eta_{P_E}^{SR}$ for $\rho > 0$.

Likewise, when the inequality $\eta_{P_E}^{SR} < \eta_{P_I}^{LR}$ holds, since both $\eta_{P_I}^{LR}$ and $\eta_{P_I}^{SR}$ are strictly positive, the income sensitivity is larger in the long run than in the short run. From Equation (A.23) and (A.40), the inequality can be expressed as:

$$\frac{\psi I}{P_E E^*_{SR}}\frac{1}{\left[1+(1-\rho)(1-\psi)\left(\frac{E^*_{SR}}{K}\right)^{-\rho}\left(\frac{\omega_K}{\omega_E}\right)\right]} < 1. \tag{A.43}$$

By assuming that we are in long-run equilibrium we can substitute in E^*_{LR} and K^*_{LR} from Equations (A.20) and (A.21). After simplifying, we end up with the following expression:

$$\rho < \frac{\psi}{\psi-1}. \tag{A.44}$$

Since, $0<\psi<1$, the right-hand side of the expression above is always negative. Hence, the inequality is only satisfied for sufficiently negative ρ. Thus, only if the goods are sufficiently complementary do we find a larger income elasticity in the long run.

A.4 From Theoretical Model to Estimation Equation

From the theory specified in Section 4, we can note that energy consumption is a function of price and income. Thus, we have:

$$E^* = f(P, I) \tag{A.45}$$

Now, introducing P^ι and I^ι , representing the long-run mean values of P and I . P and I give some value E^ι .

$$E^* = E^\iota + f_P \left[P - P^\iota\right] + f_I \left[I - I^\iota\right] \tag{A.46}$$

We can rewrite this to:

$$\frac{E^* - E^\iota}{E^\iota} = \frac{f_P P^\iota}{E^\iota}\left[\frac{P - P^\iota}{P^\iota}\right] + \frac{f_I I^\iota}{E^\iota}\left[\frac{I - I^\iota}{I^\iota}\right] \tag{A.47}$$

which corresponds to:

$$\frac{E^* - E^\iota}{E^\iota} = \eta_P\left[\frac{P - P^\iota}{P^\iota}\right] + \eta_I\left[\frac{I - I^\iota}{I^\iota}\right] \tag{A.48}$$

where η_P and η_P are price and income elasticities.

Suppose that P and I are close to P^ι and I^ι . We can then approximate: $\frac{Y - Y^\iota}{Y^\iota} \approx \ln\left[\frac{Y}{Y^\iota}\right] = \ln Y - \ln Y^\iota$ for $Y \in \{E^*, I, P\}$. Equation (A.48) can then be rewritten as:

$$\ln E^* - \ln E^\iota \approx \eta_P\left[\ln P - \ln P^\iota\right] + \eta_I\left[\ln I - \ln I^\iota\right]. \tag{A.49}$$

This can then be rearranged to:

$$\ln E^* \approx \ln E^\iota - \ln P^\iota - \ln I^\iota + \eta_P \ln P + \eta_I \ln I. \tag{A.50}$$

Thus, we have the standard demand equation as:

$$\ln E^* \approx \text{constant} + \eta_P \ln P + \eta_I \ln I. \tag{A.51}$$

Adding the vector of control variables, the estimation equation becomes:

$$\ln E^* = \alpha_0 + \alpha_1 \ln P + \alpha_2 \ln I + x'\alpha + \epsilon. \tag{A.52}$$

where $\alpha_0, \alpha_1, \ldots, \alpha_k$ are model parameters and ϵ is an error term.

B Appendix of Figures and Tables

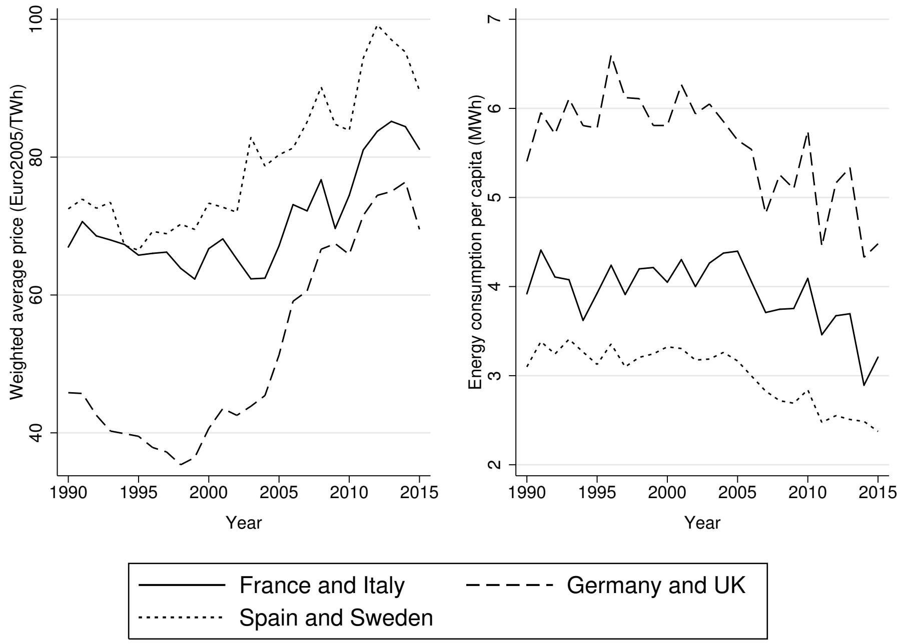

Figure B.1: Weighted average price and average energy consumption over the period 1990 to 2015 for the countries (paired by price rank). *Source: Author's own calculations. For underlying data sources see Table 5.*

Table B.1: Estimated energy demand

Variables	Total demand FE	Total demand GMM	Total demand LSDVC	Electricity demand FE	Electricity demand GMM	Electricity demand LSDVC
E_{t-1}	0.381***	0.349***	0.498***	0.731***	0.679***	0.771***
	(0.060)	(0.054)	(0.104)	(0.059)	(0.060)	(0.069)
P	−0.248***	−0.250***	−0.219***	−0.074***	−0.076***	−0.069***
	(0.031)	(0.028)	(0.040)	(0.020)	(0.020)	(0.025)
I	0.066*	0.090***	0.056**	0.059**	0.073***	0.057***
	(0.035)	(0.033)	(0.023)	(0.026)	(0.028)	(0.019)
HDD	0.449***	0.467***	0.468***	0.158***	0.170***	0.164***
	(0.047)	(0.041)	(0.055)	(0.033)	(0.032)	(0.037)
DWE	0.977***	0.970***	0.783***	0.393***	0.434***	0.328**
	(0.140)	(0.125)	(0.192)	(0.134)	(0.135)	(0.128)
PPH	0.284**	0.315***	0.252**	0.025	−0.005	0.025
	(0.131)	(0.122)	(0.103)	(0.094)	(0.099)	(0.089)
IT	−1.370*	−1.313**	−1.253	−1.305**	−1.252**	−1.209*
	(0.699)	(0.612)	(0.778)	(0.523)	(0.515)	(0.625)
$Trend$	−0.003**	−0.003**	−0.002	−0.001	−0.001	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.2: U-values

Variables	Total demand FE	Total demand GMM	Total demand LSDVC	Electricity demand FE	Electricity demand GMM	Electricity demand LSDVC
E_{t-1}	0.271***	0.272***	0.293***	0.668***	0.649***	0.710***
	(0.058)	(0.055)	(0.081)	(0.060)	(0.062)	(0.079)
P	−0.240***	−0.245***	−0.235***	−0.078***	−0.082***	−0.073***
	(0.029)	(0.027)	(0.031)	(0.019)	(0.019)	(0.024)
I	0.072**	0.070**	0.070***	0.058**	0.050*	0.056***
	(0.031)	(0.032)	(0.024)	(0.025)	(0.027)	(0.019)
HDD	0.438***	0.453***	0.441***	0.157***	0.161***	0.162***
	(0.043)	(0.040)	(0.049)	(0.031)	(0.032)	(0.037)
DWE	1.118***	1.081***	1.079***	0.489***	0.493***	0.416***
	(0.130)	(0.123)	(0.151)	(0.132)	(0.136)	(0.144)
PPH	0.120	0.200*	0.115	−0.034	−0.019	−0.034
	(0.122)	(0.121)	(0.115)	(0.092)	(0.100)	(0.093)
IT	−0.237	−0.518	−0.225	−0.915*	−1.028*	−0.802
	(0.668)	(0.621)	(0.869)	(0.516)	(0.527)	(0.677)
$Trend$	−0.003**	−0.002*	−0.003**	−0.000	0.000	−0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
UX	0.268***	0.233***	0.263***	0.119***	0.108***	0.113***
	(0.049)	(0.049)	(0.043)	(0.035)	(0.037)	(0.033)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.3: Policy categories

	Total demand			Electricity demand		
Variables	FE	GMM	LSDVC	FE	GMM	LSDVC
E_{t-1}	0.308***	0.305***	0.441***	0.709***	0.670***	0.747***
	(0.062)	(0.055)	(0.102)	(0.061)	(0.062)	(0.073)
P	−0.202***	−0.205***	−0.175***	−0.063***	−0.064***	−0.058**
	(0.036)	(0.031)	(0.031)	(0.022)	(0.022)	(0.025)
I	0.080**	0.062*	0.081***	0.075**	0.081**	0.076***
	(0.039)	(0.036)	(0.025)	(0.031)	(0.032)	(0.021)
HDD	0.441***	0.452***	0.462***	0.149***	0.151***	0.155***
	(0.047)	(0.042)	(0.053)	(0.034)	(0.033)	(0.038)
DWE	1.160***	1.111***	0.938***	0.458***	0.483***	0.393***
	(0.159)	(0.142)	(0.197)	(0.142)	(0.140)	(0.145)
PPH	0.163	0.163	0.159	0.040	−0.030	0.044
	(0.141)	(0.130)	(0.112)	(0.103)	(0.105)	(0.099)
IT	−1.340	−1.554**	−1.020	−0.903	−0.910	−0.778
	(0.834)	(0.740)	(0.984)	(0.633)	(0.616)	(0.729)
$Trend$	−0.005***	−0.004**	−0.003**	−0.001	−0.001	−0.001
	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
BHX	−0.121**	−0.121***	−0.109**	0.029	0.034	0.025
	(0.052)	(0.045)	(0.048)	(0.026)	(0.025)	(0.026)
$FIN1_{t-1}$	0.006	0.009	−0.001	−0.009	−0.006	−0.010
	(0.016)	(0.014)	(0.014)	(0.012)	(0.012)	(0.011)
$FIN2_{t-1}$	−0.029**	−0.028**	−0.024**	−0.015*	−0.014*	−0.014*
	(0.013)	(0.011)	(0.010)	(0.008)	(0.008)	(0.008)
$INFO_{t-1}$	0.009	0.008	0.010	0.006	0.006	0.007
	(0.015)	(0.013)	(0.012)	(0.011)	(0.011)	(0.010)
APP_{t-1}	0.006	0.005	0.007	−0.009	−0.011	−0.008
	(0.015)	(0.013)	(0.015)	(0.010)	(0.010)	(0.011)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.4: Filippini et al. (2014) dummy approach

	LSDVC		
Variables	Space heating	Total	Electricity
E_{t-1}	0.403***	0.283***	0.631***
	(0.052)	(0.055)	(0.063)
P	−0.197***	−0.229***	−0.073***
	(0.048)	(0.028)	(0.022)
I	0.243***	0.099***	0.063**
	(0.059)	(0.037)	(0.030)
HDD	0.912***	0.439***	0.161***
	(0.071)	(0.041)	(0.032)
DWE	0.946***	0.992***	0.467***
	(0.187)	(0.143)	(0.147)
PPH	−0.026	0.021	−0.107
	(0.249)	(0.143)	(0.111)
IT	−0.111	−1.734***	−1.163**
	(1.232)	(0.665)	(0.550)
$Trend$	−0.006**	−0.004***	−0.001
	(0.003)	(0.002)	(0.001)
$BH1$	0.001	−0.025**	0.001
	(0.020)	(0.011)	(0.010)
$BH2$	0.048*	−0.018	−0.006
	(0.027)	(0.015)	(0.013)
$FIN1$	−0.036*	−0.000	0.008
	(0.019)	(0.011)	(0.009)
$FIN2$	−0.072**	−0.035**	−0.015
	(0.030)	(0.017)	(0.013)
$INFO$	0.007	0.003	0.003
	(0.019)	(0.019)	(0.016)
APP	−0.036*	−0.004	0.002
	(0.019)	(0.012)	(0.010)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.5: Static fixed effects demand

Variables	Space heating	Total	Electricity
P	-0.344^{***}	-0.358^{***}	-0.156^{***}
	(0.055)	(0.031)	(0.027)
I	0.261^{***}	0.087^{**}	0.098^{***}
	(0.064)	(0.037)	(0.035)
HDD	0.889^{***}	0.395^{***}	0.120^{**}
	(0.094)	(0.053)	(0.048)
DWE	1.561^{***}	1.686^{***}	1.861^{***}
	(0.167)	(0.094)	(0.088)
PPH	0.414^{*}	0.403^{***}	0.180
	(0.224)	(0.128)	(0.119)
IT	2.352	-1.798^{**}	-3.919^{***}
	(1.463)	(0.803)	(0.720)
$Trend$	-0.011^{***}	-0.007^{***}	-0.004^{***}
	(0.003)	(0.001)	(0.001)
Constant	-3.567	6.425^{*}	4.480
	(6.382)	(3.395)	(2.893)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.6: Static fixed effects of energy efficiency measures

Variables	Space Heating	Total	Electricity	Space heating	Total	Electricity
P	-0.286^{***}	-0.306^{***}	-0.152^{***}	-0.185^{***}	-0.246^{***}	-0.115^{***}
	(0.058)	(0.027)	(0.024)	(0.058)	(0.037)	(0.031)
I	0.260^{***}	0.089^{***}	0.089^{***}	0.378^{***}	0.096^{**}	0.118^{***}
	(0.063)	(0.031)	(0.032)	(0.070)	(0.042)	(0.043)
HDD	0.883^{***}	0.402^{***}	0.125^{***}	0.876^{***}	0.388^{***}	0.086^{*}
	(0.092)	(0.044)	(0.043)	(0.086)	(0.049)	(0.047)
DWE	1.531^{***}	1.621^{***}	1.805^{***}	1.507^{***}	1.739^{***}	1.842^{***}
	(0.164)	(0.079)	(0.080)	(0.185)	(0.116)	(0.108)
PPH	0.235	0.184	0.063	0.118	0.156	0.082
	(0.229)	(0.111)	(0.108)	(0.259)	(0.153)	(0.146)
IT	3.314^{**}	-0.136	-2.587^{***}	3.809^{**}	-1.966^{**}	-3.440^{***}
	(1.474)	(0.709)	(0.681)	(1.592)	(0.893)	(0.841)
$Trend$	-0.010^{***}	-0.005^{***}	-0.001	-0.012^{***}	-0.008^{***}	-0.004^{**}
	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)
UX	0.273^{***}	0.364^{***}	0.264^{***}			
	(0.100)	(0.047)	(0.044)			
BHX				-0.132^{**}	-0.175^{***}	0.051
				(0.067)	(0.055)	(0.036)
$FIN1_{t-1}$				-0.038	0.015	0.003
				(0.029)	(0.017)	(0.017)
$FIN2_{t-1}$				-0.122^{***}	-0.043^{***}	-0.036^{***}
				(0.022)	(0.014)	(0.012)
$INFO_{t-1}$				0.046^{*}	0.005	0.001
				(0.027)	(0.016)	(0.016)
APP_{t-1}					0.005	-0.018
					(0.016)	(0.014)
Constant	-7.639	-1.375	-3.431	-7.502	8.667^{**}	3.140
	(6.422)	(3.030)	(2.901)	(7.066)	(3.788)	(3.410)

Robust standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$