THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Modelling drivers of energy demand in the European Union building sector

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Abstract

In the context of ongoing initiatives within the European Union (EU) to tackle global warming and to secure future energy supplies, the building sector is often cited as offering strong potential for energy savings. The primary aims of this thesis are to analyse the historical data related to EU building and to generate scenarios that highlight the technical and non-technical parameters that affect the energy demands (and thereby the potentials for savings) of the building sector.

Top-down and bottom-up approaches to modelling energy demand in EU buildings are used in the work of this thesis. In the top-down approach, econometrics are used to establish the historical contributions of the various technical and non-technical parameters related to the energy demands for heating in the residential sectors of four EU Member States. The bottom-up approach models the explicit impacts of trends in energy efficiency improvement and energy savings measures on the total energy demand in the EU buildings stock. The two approaches are implemented independently, i.e., the results from the top-down studies are not fed into those from the bottom-up studies or *vice versa*.

The explanatory variables used in the top-down modelling of energy demand are: energy prices; personal income; heating degree days, as a proxy for outdoor climate; the penetration of central heating in the building stock; energy efficiency policies in place; a time trend, which is a linear approximation for other effects, such as autonomous technical progress, fuel switching, and structural changes (e.g., change in floor area demand); and the lag in energy demand, as a proxy for inertia in the system.

The analysis of this thesis shows that increasing the floor area per dwelling and increasing consumer usage of heating and electrical appliances during the period 1970–2010 exerted upward pressure on energy demand in the European residential sector, while efficiency-related legislation and autonomous technical progress had the opposite effect. For the historical period analysed, the price elasticities of demand for energy for heating are low at around -0.3. It also emerges that during the period 1990–2010, regulations were more effective at lowering energy demand for space heating in buildings in the EU-15 than either subsidies or information campaigns. For the case of useful energy for space and water heating in the Swedish residential sector, the implicit discount rate, which is an indicator of among other things the risk level that people attach to investment decisions, e.g., efficiency measures in buildings, is calculated as 10%, i.e., 6% higher that the social discount rate that is normally applied to investment decisions.

Using the knowledge obtained from the historical analysis, to examine scenarios to Year 2050, it is shown that implementation of buildings energy efficiency legislation at the historic rate is necessary to avoid runaway growth in energy demand. Further reductions in the energy demands of buildings are can be achieved more readily with targeted measures than with price rises. This is due to market barriers that prevent a price signal having the desired effect, thereby creating the so-called ‘energy efficiency gap’. These market barriers are reflected in the low price elasticity and high discount rate outlined above. Thus, given the limited effect of price increases, it is proposed that legislated regulation of energy demand in buildings needs to be expanded, if EU-wide energy goals are to be met expeditiously.

The results of the modelling in this thesis provide a conceptual framework for the development of fiscal and regulatory policy decisions in relation to energy prices and various categories and types of energy efficiency measures, with the overall objective of meeting in a sustainable manner the future demands for energy services in the EU building sector.

List of publications

I. Ó Broin, E., Mata, É., Göransson, A., & Johnsson, F., (2013). The effect of improved efficiency on energy savings in EU-27 buildings. Energy 57:134 - 48. http://dx.doi.org/10.1016/j.energy.2013.01.016

II. Ó Broin E, Mata É, Nässén J, Johnsson F., (2015). Quantification of the Energy Efficiency Gap in the Swedish Residential Sector. Energy Efficiency 8. http://dx.doi.org/10.1007/s12053-015-9323-9

III. Ó Broin E., Nässén, J., Johnsson F., (2015). The influence of price and non-price effects on demand for heating in the EU residential sector. Energy 81: 146-58 http://dx.doi.org/10.1016/j.energy.2014.12.003

IV. Ó Broin, E., Nässén, J., Johnsson, F., (2015). Energy efficiency policies for space heating in EU countries: A panel data analysis for the period 1990–2010. Applied Energy 150: 211–23. http://dx.doi.org/10.1016/j.apenergy.2015.03.063

Eoin Ó Broin is the principal author of Papers I, II, III, and IV. For each of the four papers, the listed co-authors have contributed to the discussion and the editing of the paper. In addition, Érika Mata carried out the bottom-up modelling for Paper II.

Other publications not included in this thesis:

Ó Broin, E., Nässén, J., Johnsson, F., (2011): Future demand for space heating in buildings: a top-down analysis. EUROPEAN ENERGY PATHWAYS. Pathways to Sustainable European Energy Systems, pp. 363-367. ISBN/ISSN: 978-91-978585-1-9.

Ó Broin, E., Nässén, J., (2011): A top-down approach to modelling national energy demand: example of residential sector space heating. Methods and models used in the project Pathways to Sustainable European Energy Systems, pp. 131-135. ISBN/ISSN: 978-91-978585-2-6.

Göransson, A., Ó Broin, E., Mata, É., (2011): Future end use energy demand in the European building stock. EUROPEAN ENERGY PATHWAYS. Pathways to Sustainable European Energy Systems, pp. 345-352. ISBN/ISSN: 987-91-978585-1-9.

Lodén, J., Ó Broin, E., Johnsson, F., (2009). Towards Energy Efficient Housing – the importance of local energy planning. Proceedings of UNECE International Forum on Energy Efficiency in Housing, 23-25 November 2009, Vienna, Austria.

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I would like to acknowledge with gratitude my colleague Érika Mata for her insightful comments and co-operation in producing Papers I and II.

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1. Introduction

This thesis presents a transdisciplinary research approach to analysing the role of energy used in buildings in the EU. This research is motivated by in the context of addressing climate change, security of the energy supply, and environmental damage. The work is transdisciplinary in that it combines different streams of knowledge related to building physics, energy conversion, statistics, economics, and energy policy to reveal the key drivers and policy levers for energy use in buildings. The transdisciplinary approach is employed to address technical and non-technical research questions with regard to buildings as a part of the energy system, the economy, and society.

The thesis is organised as follows. Section 1 presents the aim of the work carried out for the thesis and introduces the topic of analysis of energy use in buildings. Section 2 provides a detailed description of the analytical tools and models that can be used to examine energy use in buildings energy systems analysis including those used for this thesis. Section 3 presents the research questions that motivated the papers of this thesis and the results obtained. Section 4 describes general criticisms of energy systems modelling in the context of the work carried out. The last two sections present the policy implications of the research and suggestions for how the work can be continued.

1.1 Aim and Scope

The aim of this thesis is to obtain an understanding of the various drivers of energy demand in EU buildings[1]. Such knowledge indicates the role of buildings in the energy system and provides insights that can be used to guide policymaking directed towards achieving sustainable energy use in buildings. The central focus of the work is the examination of the individual contributions of various technical and non-technical parameters (drivers) to energy demand in buildings. The technical parameters encompass the general effects of efficiency or intensity improvement in the energy end-uses of space heating, water heating, cooking, lighting, and electrical appliances. The non-technical parameters include building floor area, population size, and energy prices.

The scientific approach used in this thesis involves the modelling of energy use in the building stock. Here, modelling refers to using data that represent the building stock and its energy use to analyse key parameters that can explain historical energy demand and estimate future energy demand. Such modelling has traditionally been accomplished by: 1) a top-down approach, involving econometrics; or 2) a bottom-up approach, with the focus on end-uses and technologies (Bhattacharyya and Timilsina, 2009). Both approaches are used in the present work. The methodologies used, as well as their respective merits and drawbacks, are described in detail in the following sections.

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[1] The energy demands and climate impacts of the materials used in buildings or during their construction and demolition phases are not examined in this work.

This work was carried out as part of the research programme *Pathways to a Sustainable European Energy System* (Pathways Program), in which a team of researchers analyse ways to decarbonise the stationary European energy system out to Year 2050. For the buildings-focused part of the Pathways Program, the initial aim was to establish the potential energy savings up to Year 2050. This would provide knowledge for energy supply models with respect to the magnitudes of the energy demands expected up to Year 2050 under various scenarios. The key methodological departure of the Pathways Program is to include in the analysis not only new technologies, but also the existing energy system. For the buildings sector, this entails analysing the potential savings in the existing building stock rather than exploring, for example, the potential energy savings from the construction of passive housing. This is the case because in Europe the average rate of construction increases the building stock by less than 1% per year and the demolition rate is around 0.3% per year (Enper Tebuc, 2003), which means that given the >100-year lifetime of most buildings, the majority of the buildings that will exist in Year 2050 have already been built. Methodologically, this means using and analysing data that represent or model the existing building stock.

This thesis consists of this introductory essay and four scientific papers published in three academic journals (summarised in Table 1). Each of the papers examine energy use in the EU building stock from a different perspective.

Table 1 : Goals and scopes of the four papers of this thesis.

	Title	Aim	Geographic Scope	Model focus	Approach	Temporal scope	Outputs
Paper I	The effect of improved efficiency on energy savings in EU-27 buildings	Evaluate the efficiency levels needed to meet EU political Climate and Energy goals	EU-27	Total energy demand in the buildings sector	Bottom-up	2005 (Simulated) 2006 to 2050 (Estimated)	Demand projections based on efficiency improvement scenarios
Paper II	Quantification of the energy efficiency gap in the Swedish residential sector	Examine output differences from top-down and bottom-up models	Sweden	Space and water heating in the residential sector	Bottom-up and Top-down	1970 to 2005 (Modelled) 2006 to 2030 (Estimated)	Elasticities of price, income, time trend, and Heating Degree Days (HDD); energy savings per efficiency measure; demand projections based on energy price scenarios
Paper III	The influence of price and non-price effects on demand for heating in the EU residential sector	Examine the impacts of different energy prices on demand	France, Italy, Sweden, UK	Space and water heating in the residential sector	Top-down	1970 to 2005 (Modelled) 2006 to 2050 (Estimated)	Elasticities of price, income, time trend, and HDD; demand projections based on energy price and personal income scenarios
Paper IV	Energy efficiency policies for space heating in EU countries: A panel data analysis for the period 1990–2010	Evaluate three different types of efficiency policy legislation	EU-15 minus Luxembourg	Space heating in the residential sector	Top-down	1990 to 2010 (Modelled)	Elasticities of price, income, time trend, central heating, HDD, and policy

1.2 Energy Use in Buildings

Buildings account for 40% of energy use across the (EC, 2012), with industry, transport, and power systems accounting for the remainder. Energy is used in buildings to provide services, such as space and water heating, cooling, cooking, lighting, and electricity for appliances. The amounts and the proportions of energy used by each of these services are not static in time, in that they vary in line with the different drivers. Figure 1 shows that there has been an absolute increase in demand for all energy end-uses in the residential sector, with the exception of cooking, in the period 1990–2010.

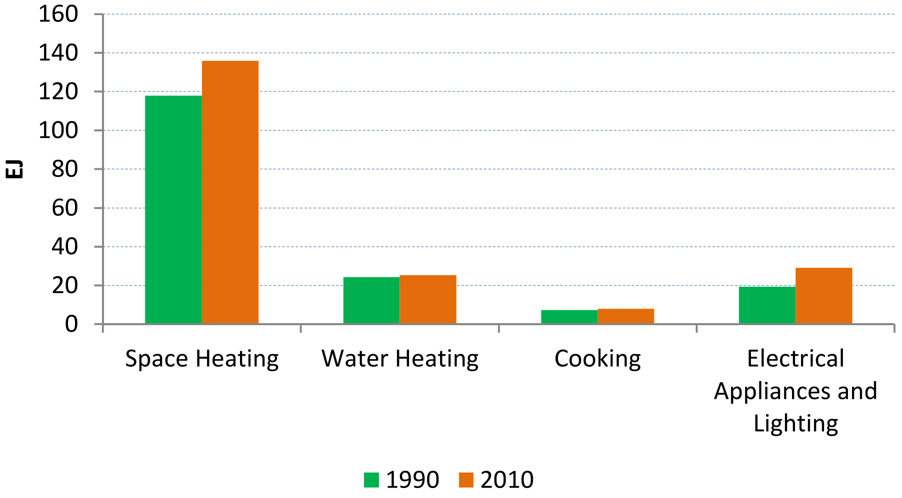

Figure 1 : Energy end-uses in the residential sector for the five largest EU countries by population (France, Germany, Italy, Spain and the UK) for the period 1990–2010. Data derived from the Odyssee Indicators Database (Enerdata, 2013).

Energy use patterns change over time (as shown in Figure 1), reflecting the dynamics of the economy and society. In simplest terms, it can be said that as population increases, demand for energy increases because more people translates to a higher energy demand. At the same time, increasing income or a growing economy entails greater demand for appliances and cars, which results in a corresponding increase in demand for energy regardless of population change. Population and income growth are non-technical drivers of energy demand in the sense that they influence energy demand irrespective of the technologies used to supply the energy. In economic jargon, population change can be described as the activity of the society, while changes brought about by increasing income, e.g., larger floor area or higher numbers of appliances, can be considered as structural effects of the economy and society, which of themselves promote changes to the energy demand. In contrast, improved energy efficiency is a technical driver of energy demand, as by improving technology it allows the same energy service to be provided for a smaller energy input and hence lowers the energy intensity of the energy service.

Figure 2 shows the Index Decomposition (Ang, 2004) (ID) of the change in residential sector energy demand in the five largest countries of the EU from 1990 to 2010. An ID is an analytical tool that is used to examine the various drivers of change in energy use across or within different sectors. In this case, ID is used to examine the drivers of energy demand in the residential sector over a period of time. For this purpose, the change in energy demand over the period is subdivided into the effects of activity change, structural change, and intensity change. These three effects (indicated in Fig. 2 as orange, green, and purple bars, respectively) combine to give the overall change (shown in sky-blue). The activity label denotes population change, to represent the additional number of people who need to be housed. The structure label reflects the design and fittings of housing, for example, changes in the floor area of dwellings or larger appliances, such as flat screen TVs. The intensity label represents the energy demand per unit, e.g., energy use per square metre of floor area, and therefore reflects how efficient the energy use in the house is.

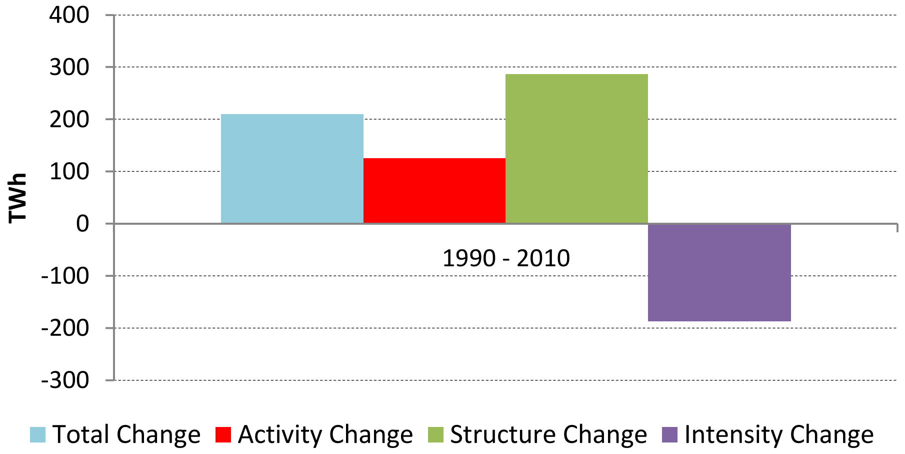

Figure 2 : Period-wise Index Decomposition of residential sector energy use for the five largest EU countries by population (France, Germany, Italy, Spain and UK) for the period 1990–2010. Data derived from the Odyssee Indicators Database (Odyssee Database, 2012) and using the Log Mean Divisia Index method (Ang, 2004).

Figure 2 shows that increasing population (activity) and increases in dwelling size and the levels of appliance ownership (structure) increased total energy demand over the period, whereas energy efficiency (intensity) measures reduced energy demand. Structural change had a 3-fold greater effect on the change in demand than did the population increase. This shows that for this period of time that increases in dwelling size and the levels of appliance ownership exerted greater influences on energy demand than did increasing population. The most important outcome shown in Figure 2 is that the non-technical drivers (population and structural change) promoted an overall increase in final energy demand, despite improvements in energy efficiency.

The decomposition presented in Figure 2 is the result of combining various indicators that describe the energy use within a sector of the economy. For example, energy intensity is expressed as energy demand per unit of floor area (kWh/m^2/year, also known as unit consumption), and it is a widely used indicator of progress in the energy efficiency of buildings, i.e., decreases are inferred to reflect improvements in energy efficiency. The use of such indicators to describe the energy system is analogous to using an indicator such as blood pressure to describe human health. Indicators that relate to energy use in buildings include: energy demand per unit of floor area; per capita energy demand; and energy use per appliance. In addition, examples of non-technical indicators are: population, given that population reflects the number of people that need to be housed; and floor space per capita and per-capita ownership of appliances, as these two parameters reflect the standard of living of the population. Analysis of these indicators can facilitate the formulation of policy, in the sense that the various parameters are ranked in terms of their contributions to overall energy demand. From the example shown in Figure 2, it is apparent that to achieve an overall reduction in energy demand in buildings in the five largest countries of the EU, efficiency needs to be further improved or dwelling and appliance sizes have to be curtailed or all of these measures need to be implemented.

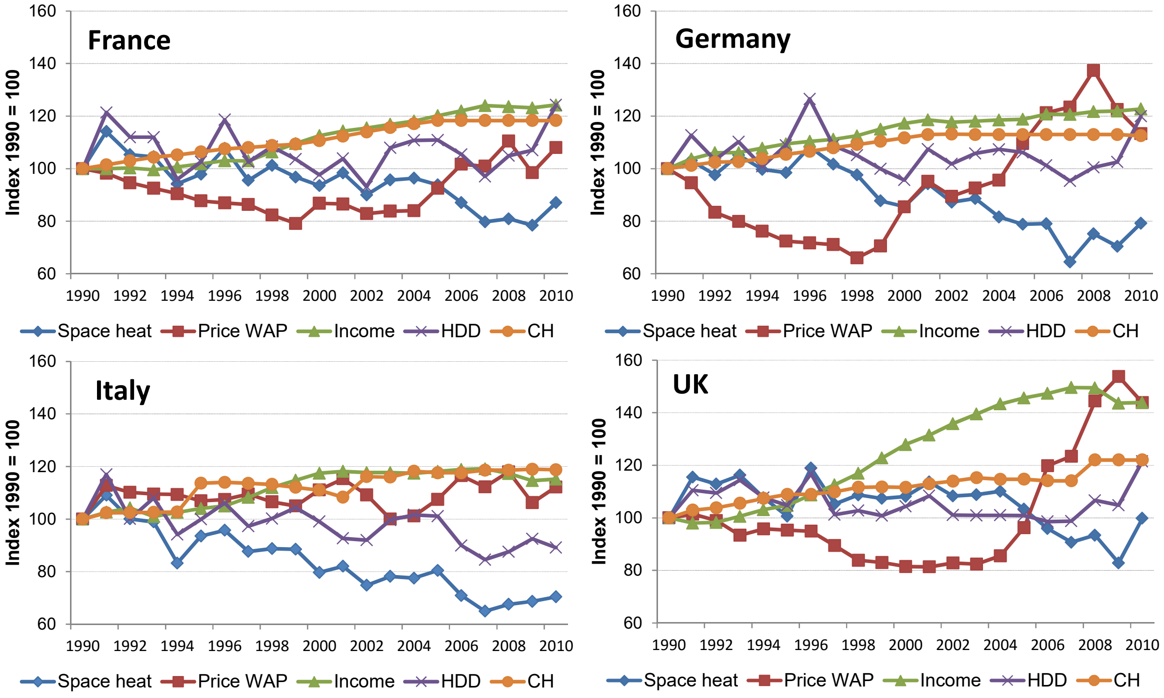

Figure 3 : Index of space heating demand and determinants of its dynamics (including HDD and penetration of central heating) for four large EU countries (Paper IV, Figure 2).

However, as suggested above, indicators do not change independently of the economy and society in which they exist. Floor space per capita and per capita ownership of appliances can be related to other parameters, such as growth in GDP or personal income. Figure 3 shows how income and other important drivers of energy use in buildings have evolved in four large EU countries between 1990 and 2010. In each country, the average income has increased over the period, and by as much as 50% in the UK. This example of income shows how the dynamics of the energy system must be understood in the context of macroeconomic developments.

Energy use in buildings is important in the context of EU Climate and Energy goals. Lowering the absolute energy demand is a stated key policy goal of the (EC, 2012). This is to be achieved mainly through improvements in end-use efficiency (EC, 2011). The indicative goal for Year 2020 is to lower the primary energy demand in the EU by 20% relative to a business-as-usual scenario (EC, 2012). For the residential sector, the energy savings target has been set at the higher level of 27% due to the well-documented opportunities for savings in this sector (EC, 2006). These efficiency goals are part of the EU Climate and Energy Packet (known colloquially as the EU 20 20 20 goals), and also include the goals that by Year 2020 there should be a 20% share for renewables in the energy supply systems and a 20% reduction in greenhouse gas emissions (relative to the levels in Year 1990) (EC, 2008). The greenhouse gas and renewables goals for Year 2020 are expected to be met, while that for savings from efficiency (which is non-binding) is not expected to be met (EC, 2014). In Year 2015, goals for Year 2030 were also adopted. These include: a 40% cut in greenhouse gas emissions compared to 1990 levels; at least a 27% share of renewable energy consumption; and at least 27% energy savings compared with the business-as-usual scenario. The first of these three targets is the intended nationally determined contribution (INDC) that the EU has pledged to achieve as part of the COP21 treaty negotiations in Paris in late 2015 (EC, 2015). The third target can be seen as a 7% improvement on the savings from efficiency target for Year 2020. It emphasises that for sectors such as housing that there will be a need for significant acceleration of current efforts to tap the significant unexploited potential, and that this will require large investments in the building sector (leading to lower running costs) (EC, 2014).

Energy use in buildings is also important for other reasons, such as security of supply. An improvement in the heating energy efficiency of buildings across the EU would reduce dependency on imported natural gas from countries such as Russia, Algeria, and Norway. In fact, different stakeholders promote many different focus areas for energy efficiency. These go beyond security of supply and mitigating climate change to include reducing the volatility associated with oil prices, increasing the competitiveness of the economy by reducing energy costs, stimulating employment in the construction sector, improving both indoor and outdoor air quality *via* improved ventilation and decreased emissions of combustion gases, and reducing noise pollution by improving insulation. There is undoubtedly some overlap among these policy goals, resulting in ‘co-benefits’, which are the bonuses acquired from implementing policy measures to tackle climate change or increasing efficiency to reduce energy demand.

2. Energy System Modelling for Buildings

This section presents a general introduction to Energy System Modelling for Buildings. This is followed by sections focused on top-down and bottom-up modelling. When relevant, reference is made to the modelling undertaken in this thesis.

Over the past 50 years, computers have become smaller in size and faster, while at the same time digital signal processing has enabled the handling and storage of large volumes of data. Together, these developments have facilitated the creation and maturation of computer modelling. (Sterman, 1991) pointed out that computer models have been used to analyse everything from the performance of national economies, to the optimal distribution of fire stations in New York City, to the interplay of global population, resources, food, and pollution, and they have become commonplace in forecasting and public policy analysis, especially in the fields of economics, energy and resources, and demographics. Applied to policy endeavours related to energy, one can say that computer modelling has allowed for quantitative analyses that can, for example, uncover patterns and trends in energy demand and generate scenarios for how trends will develop.

Computer models of energy supply and demand have evolved into two broad classes: top-down and bottom-up (Lanza and Bosello, 2004). Top-down models take a country, a region, a sector or a type of energy end-use (e.g., space heating) as their start-point, and thereafter model energy supply or demand as it relates to economic parameters, such as energy prices and personal income. These economic relations are themselves often grounded in the theory that market clearing restores a supply and demand equilibrium to the economy after price changes. Thus, top-down models can estimate the expected outcome of an energy price change. If the economic relationships included in the model cover the entire economy, such models are termed ‘general equilibrium models’[2], while if they isolate only one sector (e.g., the energy sector), they are known as ‘partial equilibrium models’. In the former case, energy is one of the factors in a function, e.g., a production function or utility function, whereas in the latter case, energy supply or demand is the subject of a function. In both cases, the responses of demand or supply to changing energy prices are inherent to the models (Nystrom and Wene, 1999). The rates of change in supply or demand subject to changes in energy prices are established using exogenous elasticities calculated from historical time-series data (see Section 2.2). For general equilibrium models, the endogenous change in demand for the respective fuels is then related to the rest of the economy. Typical policy changes that can be modelled using top-down models (where price is the parameter that changes) are: nuclear phase-out; green quotas; and environmental tax reforms (Böhringer and Rutherford, 2008). In the case of nuclear phase-out, for example, a relatively cheap electricity supply option (nuclear) would have been removed from the production function, thereby increasing electricity prices and the demand for the other fuels in the model. The change in the level of greenhouse gas emissions could also be included in the model by incorporating a factor that

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[2] Derived from the neo-classical theory of general equilibrium established by Arrow, Debreu and others (Sanstad and Greening, 1998)

accounts for the carbon content of the fuels. Conventional top-down models represent technological change as an abstract, aggregate phenomenon, which means that they mostly help policymakers to assess only economy-wide policy instruments, such as taxes and tradeable permits.

Bottom-up models can also take a country, a region, a sector or an energy end-use as their start-point. However, instead of exploring energy demand in the context of economic factors, bottom-up models utilise a rich technological description (which can be organised as a database) of the energy supply and energy use technologies that comprise the energy system. If the scope of the model is sufficiently broad, it can be described as using a systems approach[3]. These models represent the interactions of the multiple components of the energy system based on mathematical formulations. Optimisation or simulation techniques are typically used to model the interactions that occur between the technical components in a bottom-up model (Sorrell et al., 2004). Optimisation[4] can be used to select a minimum-cost technical solution for, e.g., a carbon emission constraint, and simulation models can be used to rank technological choices in terms of different criteria, such as cost, energy savings or carbon emission reductions.

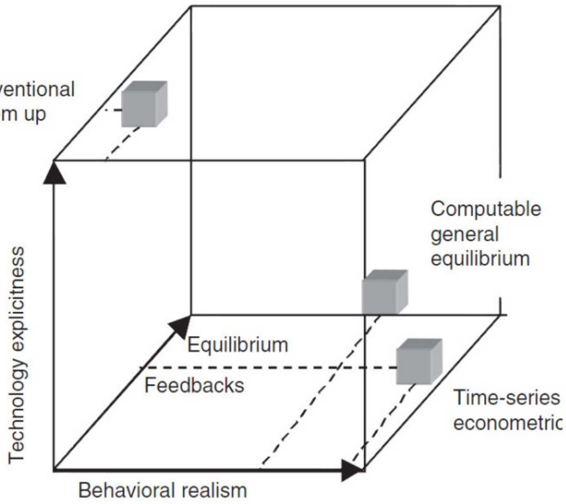

Figure 4 : Parameters inherent to an ideal Energy Economy Model (Jaccard, 2009).

The main differences between the top-down and bottom-up approaches are that the former are anchored in the economic relationships of the economy but say little about technical solutions, while the latter are not anchored in a macroeconomic setting but are technology explicit. This has led to the development of hybrid models that incorporate features of these two approaches or that use top-down and bottom-up models in tandem. In the latter approach, the models are

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[3] A system is a set of elements that are connected to form a whole, with the consequence that the system possesses the properties of the whole rather than those of its component parts (Nakata et al., 2011) citing Checkland.

[4] (Sanstad and Greening, 1998) describe how optimisation models originate from the refinements made by Caas and Koopmans in the 1960's to Ramsey's neoclassical theory of growth.

hard-linked (*via* computer code) or soft-linked (by manually feeding outputs from one approach into the other). It has been stated (Jaccard, 2009) that policymakers need models that: 1) can evaluate the effects of economy-wide policies working in concert with technology- and fuel-specific measures; and 2) incorporate regulations as well as market-based policies. Thus, Jaccard has proposed that the ideal model (Figure 4) has technology explicitness and economic behavioural realism (of consumers, firms and other market actors), which are linked to the dynamics of the overall economy (Jaccard, 2009). Efforts to create a model that has all these features range from the Markal-Macro model of (Nystrom and Wene, 1999), in which a detailed bottom-up model is combined with a simplified economic model, to Böhringer and Rutherford's Computable General Equilibrium energy-economy model (Böhringer and Rutherford, 2008), which integrates bottom-up activity into the analysis. Despite these efforts, most modelling of energy systems involves either the top-down or bottom-up approach. This may reflect the fact that the specific research questions being addressed do not require the all-encompassing view that hybrid models provide. In Papers III and IV of this thesis, for example, the calculation of energy demand price elasticities was considered to be important, and these values are best calculated with partial equilibrium top-down models. The following two sections introduce top-down and bottom-up modelling systems in more detail and describe the specific modelling methodologies used in this thesis.

2.1 Bottom-up (Engineering) modelling of energy demand in buildings

As described above, bottom-up modelling starts with a technical description of the building stock, and thereafter models the relationship between the described technical parameters and the energy demand. These interactions can be modelled within the context of, for example, an energy savings goal or an energy price regime. The level of detail used to describe the building stock and the mathematics of the modelling relationships used vary. In a review of techniques for modelling end-use energy consumption in the residential sector, (Swan and Ugursal, 2009) distinguished six types of bottom-up models (Statistical Regression, Statistical Conditional Demand Analysis, Statistical Neural Network, Engineering Population Distribution, Engineering Archetype, and Engineering Sample). In this thesis, both the Engineering Archetype and Engineering Sample approaches have been used. For these approaches, the building stock is described by a number of representative or archetypal buildings or by a sample of the buildings. In the former case, the archetypal buildings consist of averages for the various parameters that describe the stock, whereas in the latter case, a technically detailed sample of the building stock is used.

For the purposes of describing the scope of typical space heating-focused bottom-up models, the energy demand functions for four example models are described below. These include the two bottom-up models that are used in the work carried out for this thesis (in Papers I and II, respectively) and two other engineering-type models. The latter two models are included for the purpose of contextualising the two bottom-up models used in this thesis. Each of the four demand function equations calculates a technical energy savings potential from efficiency improvements, while three of the equations additionally calculate a cost-effective or profitable level of potential energy savings from the same measures. The key differences between the models are the decision criteria used to promote efficiency improvements, i.e., the factors used to decide whether or not an improvement in efficiency is cost-effective. To describe the differences between the four models, a general space heating final energy demand function made up of five parameters, (a) to (e), is used in Eq. (1), which provides an example of the various parameters and indicators that can be used to describe energy use in buildings at the aggregate national or regional level. This is relevant given that the work of this thesis focuses on energy demand at the national (EU Member State) or regional (EU) level.

$$F_t = A_t . B_t . C_t . D_t . E_t \tag{1}$$

where A is the number of dwellings, B is the floor area per dwelling, C is the useful energy demand per floor area per degree day, D is the number of degree days, E is the conversion efficiency, F is the Final Energy Demand, and t is the time-step in years. Equation (1) is based on the IPAT equation[5] (Ehrlich and Holdren, 1972) with the I in IPAT being equivalent to the F parameter in Equation (1), P being equal to A, A being equal to B, and T being equal to the product of C, D and E. In Eq. (1), C describes the efficiency of the building envelope, while E describes the efficiency of energy conversion. The other parameters in Eq. (1) are drivers of the demand for energy services, e.g., the climate (as represented by degree days) and the size of the dwelling.

The first of the four demand functions presented is described by Eq. (2) and is used in Paper I of this thesis:

$$E_t = E_{t-1}(1 - D_t)(1 + S_t)(1 - F1_t - F2_t - F3_t) \tag{2}$$

where E is the total demand of energy for heating (in TWh), D is the demolition rate (in %), S is the standard increase (in %), $F1$ represents the continuous improvement in efficiency measures (in %), $F2$ represents once-off efficiency measures (in %), $F3$ represents renovation cycle efficiency measures (in %), and t is a discrete time-step (in years). Comparing Eq. (2) to the general demand function in Eq. (1), A to D from Eq. (1) are combined into one metric (E_t) on both sides of Eq. (2). Thus, Eq. (2) models useful energy demand and has no need for a parameter to convert from useful to final energy [E from Eq. (1)]. The focus of this energy demand function is on general rates of efficiency improvement rather than on individual measures. For example, the approach calculates the percentage improvement in the efficiency of space heating that is needed to meet a policy goal rather than say evaluating different levels

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[5] In the IPAT formulation: I = Impact; P = Population; A = Activity; and T = Technology. The idea is that the *impact* on the planet of a social practice can be decomposed into trends in *population* change, the *activity* of the population, e.g., housing, length of shower, length of car trip, and the efficiency of the *technology* used in the activity. Note that the IPAT formulation is slightly different from the Index Decomposition (ID) presented in Figure 2, as 'Population' in the IPAT corresponds to 'Activity' in the ID and 'Activity' in the IPAT corresponds to 'Structure' in the ID.

of insulation improvement. In the model in which Eq. (2) is used the level of disaggregation at the building level is simply between single-family and multi-family dwellings and between existing and new builds for both categories. This entails the building stock being divided into four archetype buildings. Technology-neutral efficiency improvement rates (*F1* to *F3*) are presented as aggregate percentages. These efficiency improvement rates are exogenous model inputs, which means that the decision criteria for implementing efficiency improvements are also exogenous. In Paper I, the goal was to estimate the energy savings potential for the EU as a whole. Given this wide geographic scope, the model cannot have too many parameters, otherwise it would risk being overly data-intensive; in addition a cost component is not deemed to be necessary.

The second of the four energy demand functions comes from Ecofys (Petersdorff et al., 2005) and uses a simple equation [Eq. (3)] to calculate the energy savings potential associated with adding insulation to a dwelling.

$$\vartriangle E = HDH * \vartriangle U * 1/\eta \qquad (3)$$

where ΔE is the change in final energy savings per building floor area (in kWh/m^2/year), HDH is the total Heating Degree Hours (in kKh/year) for a region, ΔU is the difference between the U-values before and after retrofitting (in W/m^{2}K), and η is the conversion efficiency of heat generation and distribution (in %). The focus in the Ecofys model is on retrofitting measures which lower the U-value. The criterion used to decide whether to implement a measure that would lead to an increase in ΔU is based on the lifecycle cost of the measure versus the cost of the energy saved. As ΔE represents the change in final energy savings per building floor area, it's equivalent in the energy demand function is the change in parameters C to E brought about by a change in U-values (a sub-component of C). On the right hand side of Eq. (3) parameter D from the energy demand function is equivalent to HDH, while the change in the parameter C (caused by a change in U-value) and E are represented as ΔU and η, respectively. Compared to Eq. (2), Eq. (3) is more technically explicit as it changes demand via changes in U-values that can be related to insulation standards rather than via general rates of efficiency improvement as Eq. (2) does.

The third of the four energy demand functions [Eq. (4)] is taken from a previous publication (Mata et al., 2013); it is employed in Paper III of this thesis and is used to describe useful energy demand for a single building:

$$q = C_m . \frac{dT_{int}(t)}{dt} + q_t(t) + q_v(t) - q_r(t) - q_{int}(t) \qquad (4)$$

where q is the total heat provided by the heating/cooling system [in watts (W)], C_m is the effective internal heat capacity of the building (in J/K), T_{int} is the indoor air temperature (in °C), q_t is the transmission-related heat losses through the building envelope (in W), q_v is the ventilation heat loss (in W), q_r is solar radiation gains through windows (in W), and q_{int} is total internal heat gains (in W). Equation (4) is part of the ECCABS (Energy, Carbon and Cost Assessment for Building Stocks) model (Mata et al., 2013). In the ECCABS model, Eq. (4) is applied to a high (>1000) number of individual buildings that are chosen to be representative of a building stock. In Eq. (4), the emphasis is also on the influences of individual technical measures on energy demand, albeit at a higher level of detail than that of the Ecofys model given in Eq. (3). Parameters B to D from Eq. (1) are combined into a single metric, q, on both sides of Eq. (4), except that on the right-hand side, q is disaggregated into four parts, as presented. The influences of efficiency improvements on parameters C_m, q_t, q_v, q_r are modelled. The criteria used to decide whether to implement a measure that would lead to a decrease in q_t *or* q_v, or to an increase q_r are based on the lifecycle cost of the measure versus the cost of the energy saved. In Paper II, the goal is to estimate the potential for energy savings in Sweden. This narrower geographic scope (as compared to that in Paper I) allows for a more detailed model and the inclusion of cost criteria.

The fourth of the four energy demand functions described is from a previous paper (Giraudet et al., 2012). In that model, the heating energy demand changes for each model iteration subject to a *proportion of the building stock undergoing an energy-efficient renovation*, as well as to a utilisation factor that accounts for the so-called rebound effect. The utilisation factor is a combination of psychological, cultural, and lifestyle preferences, which are captured *via* price signals and empirical measurements. The model is a hybrid in that the energy prices, which are one of the parameters determining the level of renovation and utilisation, are derived recursively *via* a hard-linked Computable General Equilibrium (CGE) model. The CGE model also provides income levels, which are one of the determinants of the building construction rate. The demolition rate is exogenous. Thus, for this model, parameters A to E from Eq. (1) are combined into a single metric on the left-hand side of the model energy demand function (not shown), while the right-hand side is disaggregated into $A+B$ (total floor area), $C+D$ (useful energy per square metre), and E (conversion of useful energy into a fuel mix). The parameter of useful energy per square metre is further subdivided to account for the proportion of demand linked to the rebound and utilisation patterns. The decision criterion for the proportion of the stock that is renovated is subject to the following function parameters:

Proportion of buildings undergoing renovation = f(investment cost, running cost, intangible cost)

- Investment cost: incorporates technology purchase and installation costs. These costs decrease through learning but increase marginally the higher up the efficiency ladder a renovation goes.

- Running Cost: the discounted cost of energy and maintenance for a technology. The discount rates differ depending on whether the building is owner-occupied or rented and multi-family or detached.

- Intangible cost: incorporates hidden costs that result from transaction costs, imperfect information, bounded rationality, consumer preference etc. These costs decrease (following a logistic fit) as more of the dwelling stock is renovated, through what is known as “the neighbour effect”.

(Giraudet et al., 2012) used these criteria in a building stock model for the residential sector in which the stock was divided according to: (i) efficiency class; (ii) heating energy carrier used; and (iii) whether the dwellings were multi-family or single-family.

The four model energy demand functions presented above range in terms of detail from Eq. (2), which has no cost criteria for energy demand change, to the fourth described model, which has a cost criterion but also incorporates rebound and economic equilibrium effects. Equation (2) is applied to the entire stock of buildings for the EU, whereas the fourth model is applied to the French Residential Sector. This variety of spatial scopes explains why the fourth model is much more detailed than the first model. Combining the data to apply the fourth model to the EU building stock would be very data- and time-intensive. For the purposes of the work carried out for this thesis, the first [Eq. (2)] and third [Eq. (4)] energy demand functions described above have been used in Papers I and II, respectively. These choices of models were made based on the research question being addressed, the available data, and the desired geographic scope (See Table 1). The research questions (as listed in the *Aim* column of Table 1) are discussed in more detail in Section 3. The energy demand functions that are described above but not used in this thesis (Petersdorff et al., 2005) (Giraudet et al., 2012) could be utilised in future work.

2.2 Top-down (Econometric) modelling of energy demand in buildings

A key feature of the work described in Papers II, III and IV of this thesis is the use of linear regression techniques to establish econometric relationships. This generates the elasticities, which are essential features of top-down models. These elasticities are calculated in the context of production functions for different energy end-uses, such as space heating. Using the approach described previously (Alberini and Filippini, 2011), a production function for an energy service S (e.g., space heating) can be described as[6]:

$$S = S(E, CS) \qquad (5)$$

where E is energy use and CS is the capital stock consisting of heating equipment. The term for energy service, S, in turn enters the utility function of the household, U, as an argument, along with aggregate consumption, X. The utility function is influenced by household

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[6] For a review of econometric studies of energy demand in the residential sector using household production theory see (Madlener, 1996).

characteristics, Z, as well as by the weather in the area in which the household is located, W, and the design of the house itself, D. Formally,

$$U = U(S(E, CS), X; Z, W, D) \tag{6}$$

The household is assumed to maximise utility subject to a budget constraint:

$$Y - P_s.S - X = 0 \tag{7}$$

where Y is the money income and P_S is the price of the energy service. The solution to this optimisation problem yields demands functions for E, CS, and X, which describe the long-term equilibrium of the household. For E, the function is:

$$E = E(P_s, Y; Z, W, D) \tag{8}$$

This model is static in the sense that it assumes an instantaneous adjustment to new equilibrium values when prices or income levels change. Specifically, it is assumed that the household can change both the rate of utilisation and the stock of heating equipment and the dwelling thermal efficiency, adjusting these parameters instantaneously and jointly in line with variations in prices or income, so that the short-term and long-term elasticities are equivalent. Based on Eq. (8) and using a log–log functional form, a static empirical model of household heating demand can be written as:

$$ln(E_t) = C + ln(P_t)\,\beta 1 + ln(Y_t)\,\beta 2 + ln(HS_t)\,\beta 3 + (HDD_t)\beta 4 + (t)\beta 5 + \varepsilon_t \tag{9}$$

where E_t is the total energy demand for space heating (an energy service), P_t is the weighted average price (WAP) for energy, Y_t is income per capita, HS_t is household size, HDD_t is heating degree days, t is a time trend that represents evolution in dwelling efficiency brought about by autonomous technical progress and legislation, ε_t represents residual effects not captured in the model, and C is a constant. Since energy consumption and the regressors are in logarithmic form, the coefficients ($\beta 1$ to $\beta 5$) are directly interpreted as demand *elasticities*. However, actual energy consumption would differ from the long-run equilibrium consumption, since the equipment and dwelling stock cannot adjust easily to the long-run equilibrium. This warrants the inclusion in Eq. (9) of a lagged term, $ln(E_{t-1})\,\beta_6$, which captures this effect and makes the regression autoregressive and dynamic. Autoregressive refers to the feedback inherent to the regression by including a lagged dependant variable. Lags of the explanatory variables can also be included, for example, lags of income or price. Such lags are called ‘distributed lags’. Thus, the inclusion of both autoregressive and distributed lags creates an Autoregressive Distributed Lag (ARDL). Historically, the ARDL model has been the most commonly used econometric model to describe energy demand (Bentzen and Engsted, 2001).

The elasticities, β_1 to β_6, in Eq. (9) are typically obtained by the method of ordinary least squares (OLS) (Gujarati and Porter, 2015). The input data for Eq. (9) are typically time series annual averages for the respective parameters. As with the modelling described above, the time series are specific for a country, a region, a sector or an energy end-use. However, if these time series do not have the property of being stationary, the calculated elasticities are prone to being spurious (inaccurate). In other words, for the results obtained from OLS regression to be valid, the variables used must be stationary. A stochastic process is deemed to be stationary if its mean and variance are constant over time (Gujarati and Porter, 2015). In the literature, the Unit Root Test is often used to assess if a time series is stationary or not. The most commonly cited Unit Root Test is the Augmented Dickey-Fuller (ADF) test. This test is carried out by running the following autoregressive process regression for any time series under examination:

$$\vartriangle(X_t) = X_0 + \lambda(t) + \varepsilon(X_{t-1}) + \delta \vartriangle (X_{t-i}) + U_t \tag{10}$$

where X_{t-i} represents an undetermined number of augmentation lags to be included in the regression, t is a time trend, and U_t represents the residuals from the regression. Enders (2004) has proposed that these lags, e.g., $\delta\Delta$ (X_{t-i}), should be included to ensure that U_t, which is a white noise process, is not serially correlated. He has also suggested that one approach to guaranteeing this is to start with a long lag length and thereafter pare down the model to only include lags that are significantly different from zero. The time trend, t, is included in case a long-term trend falsely suggests non-stationarity. The essence of the ADF test itself is to examine whether or not the value of ε is significantly different from zero, i.e., whether the past is influencing the present. Critical t-statistics for ε are of no use if X_t is not stationary, although other statistical measures that follow the Dickey- Fuller distribution have been tabulated for explicit use with the Unit Root Test (Gujarati and Porter, 2015). When ε is found to be significantly different from zero one can conclude that X_t is a non-stationary time series, and that there is persistent accumulation of past effects (Hendry and Juselius, 2000). This is usually the case in economic time series. (Madlener, 1996) has written that a common solution for the non-stationarity of data is the differencing of variables before running regressions. However, Madlener has also pointed out that this approach suffers from the important drawback that long-run properties of the data are lost, thereby restricting the models to explanations of exclusively short-run effects.

Cointegration Analysis then comes into play as a method for deriving a long-term relationship between non-stationary variables. (Silk and Joutz, 1997) cited a previous study (Engle and Granger, 1987) in explaining that even if all or a subset of the dependent and explanatory variables are non-stationary, there may exist a linear combination of these variables that is stationary. This linear combination expresses a long-run equilibrium relationship. Put another way, although the individual variables used may not have constant mean and variance over time, if they are nonetheless tracking each other they may have a common long-run cointegrated relationship that can be modelled in a form that represents an alternative to linear

OLS regression in levels[7]. If this is the case, a co-integration vector that represents the long-run relationship between the variables in levels can be combined with the same variables in differenced form for the purposes of OLS regression.

Such a combination is the essence of the Error Correction Model (ECM), in which the short-run dynamics of the variables (as represented by variables differenced to make them stationary) have their long-run trajectory steered or "corrected" by their co-integration vector. In the ECM, error correction is carried out using a rate of adjustment coefficient. This will correct short-term overshoots and undershoots or any shocks back towards the long-term equilibrium. A price increase is an example of such a shock that can lead to an over- or under-shoot. Enders (Enders, 2003) has warned however that the value of the rate of adjustment coefficient should not be too high, making the point that the larger the value the greater proportion of the error correction is undertaken in the first year after the shock. (Enders, 2003) has suggested that rapid (within 1 or 2 years) correction may not be realistic, and that the correction of overshoots and undershoots need not be instantaneous but can occur over the long run. To determine if a co-integration vector exists between a set of variables, the errors (residuals) from an OLS regression of the variables in levels is tested for stationarity. The ADF Unit Root Test [Eq. (6)] can also be used for this purpose (Enders, 2004). Specific critical values for ε for this case of the ADF are available in a previous publication (Gujarati and Porter, 2015). Since the beginning of the 1990s, co-integration analysis has become the standard component of all energy studies using time-series data (Athukorala and Wilson, 2010). In this regard, pioneering co-integration analysis work has been conducted by (Bentzen and Engsted, 1993), who have demonstrated the use of an ECM to calculate the short- and long-term price elasticities of energy demand in Denmark. The same authors however cite another study (Pesaran and Shin, 1999) to update their 1993 work (Bentzen and Engsted, 2001) to show that that the ARDL model can be used for the same purpose, as long as the underlying variables are cointegrated. This method is applied in Papers II and III of this thesis.

Time series for more than one entity (e.g., country) can also be combined into what is known as a panel, and the average elasticities for the combination can be obtained. This may be useful if one wants to for example use the data for individual EU countries to obtain the average elasticities for the EU. Panel data econometrics are used in Paper IV. The econometrics of panel data are slightly different those shown in Eq. (5), as the possibility exists to take cognisance of the unique characteristic of the individual entities in the calculations. In panel data econometrics, the unique features of the entities can be captured by calculating separate constants [C in Eq. (9)] for each entity. Depending on the assumptions made regarding the correlation between C and the errors of the panel, e_{it}, the panel data regressions can be defined as being fixed or random. However, for work involving individual countries, fixed panels are usually chosen because the choice of the entities (countries) is not

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[7] Levels here is jargon to describe where all the variables in a regression are the original time series e.g. not their differences. The order of integration of a time-series, denoted I(d), shows the number of times it needs to be differenced to be made stationary e.g. a I(1) time-series needs to be differenced once to become stationary.

random (Dougherty, 2011). Cointegration analyses of panel data econometrics are not widely used as this topic is still under development.

Table 2 shows a selection of studies that have applied ARDL, ECM or Panel Data econometric methodologies, including those from Papers II, III, and IV of this thesis. A variety of explanatory variables has been used: while some papers have focused on individual energy carriers, others have focused on energy or electricity demand. The price elasticities of demand shown are typical for the residential sector, i.e., negative polarity and inelastic (<1).Table 2 also shows the error correction terms obtained with the ECM models. The error correction term shows the number of years needed for the system to return to its long-term equilibrium following a shock, e.g., a price increase. In the first example shown in Table 1, it would take 3 years to return to long-term equilibrium given that 0.37 of the shock is corrected each year. This correction works because the explanatory variables are cointegrated, i.e., they have a long-term relationship, as described in the previous paragraphs. The results presented in Table 2 are important and fundamental to econometric energy system modelling because they not only describe what has happened, e.g., how big an impact price changes had on demand, but they also provide key parameters for modelling future energy demand.

There are many variations on the model presented in Eq. (9). Other groups (Alberini and Filippini, 2011) and (Douthitt, 1989) have also included the price of an alternative energy carrier in their econometric formulations. The idea is that the price of a substitute for the composite energy commodity should be included so as to calculate cross-price elasticities and to show how the price dynamics of an energy commodity has an impact on an alternative and *vice versa*. (Douthitt, 1989) included variables that are described as being related to economic, structural, thermal, internal design temperature, and human/capital factors in order to estimate more accurate price elasticities. Douthitt also estimated the alternative price elasticities for households that pay higher or lower than average energy prices. (Haas and Schipper, 1998) and (Nässén et al., 2008) replaced the total demand, E_t, in Eq. (9) with unit consumption (kWh/m^2/year or kWh/capita/year), in order to *clean* the influences of changes in floor area per household or population from the regression function. Their approach is adopted in Papers II, III, and IV of this thesis. (Adofo et al., 2013) have provided a review and analysis of the case for asymmetric price responses (APRs), that is price elasticities that are different for rising and falling energy prices. The model that they present, which has been used over the last two decades in the discourse on asymmetric prices, contains three price variables: P_{max}, P_{rec}, and P_{cut}, which represent prices above the previous maximum, a price recovery below the previous maximum, and a price cut, respectively. Asymmetric price elasticities are not investigated in this thesis but could be examined in future studies.

Table 2 : Selection of scopes and results obtained from studies using ARDL, ECM, and Panel Data econometric modelling.

Reference	Geographic and Temporal Scopes	Dependent Variable	Explanatory Variables	Methodology Applied	Short-Term Price Elasticity	Long-Term Price Elasticity	Error Correction Term
(Silk and Joutz, 1997)	USA 1949 to 1993	Electricity Demand in the Residential Sector	Electricity price, Income, Outdoor temperature, Mortgage interest rate, Real distillate fuel oil price.	ECM[c]	-0.48	-0.63	-0.37
(Madlener, 1996)	Austria 1970 to 1993	Energy demand in Residential Sector	Price, Income, Outdoor temperature	ECM	N/A	-0.021	-0.78
(Fouquet, 1995)	UK 1974 to 1994	Energy demand per energy carrier in Residential Sector	Average price of energy relative to other products, price of individual fuels relative to average price of energy, Income, Outdoor temperature	ECM	- 1.22(C),[a] - 1.01 (E), - 1.64 (P), - 0.50 (G)	-0.73 (C), -0.39 (E), -1.71 (P), 0.92 (G)	-0.37(C), -0.94 (E), -0.82 (P), -0.71 (G)
(Athukorala and Wilson, 2010)	Sri Lanka 1960 to 2007	Electricity demand in Residential Sector	Electricity price, Gas price, Kerosene price, GDP per capita	ECM	-0.16	-0.62	- 0.12
(Nässén et al., 2008)	Sweden 1970 to 2002	Space and water heating demand per floor area in Residential Sector	Price, Income, Time trend	ARDL[D]	- 0.21 (SFD)[b] - 0.07 (MFD)	- 0.31 (SFD) -0.40 (MFD)	N/A[E]
(Haas and Schipper, 1998)	OECD-11 1970 to 1993	Energy Demand per floor area in Residential Sector	Price, Income, Outdoor temperature	ARDL	- 0.09 to - 0.11	- 0.11 to - 0.33	N/A
This thesis; Paper II	Sweden 1970 to 2005	Space and water heating demand per floor area in Residential Sector	Price, Income Lag, Outdoor temperature, Time trend	ARDL	-0.15	-0.29	N/A
This thesis; Paper III	France, Italy, Sweden, UK 1970 to 2005	Space and water heating demand per floor area in Residential Sector	Price, Income, Lag, Outdoor temperature, Time trend	ARDL	-0.060 to - 0.21	-0.17 to - 0.35	N/A
(Filippini et al., 2014)	Panel of 26 EU countries 1996 to 2009	Energy demand in Residential Sector	Price, Income, Population, Dwelling Size, Outdoor Temperature, Time Trend, Efficiency Policy	Panel Data	-0.19 to-0.26		N/A
This thesis; Paper IV	Panel of 14 EU countries 1990 to 2010	Space heating demand per floor area in Residential Sector	Price, Income, Outdoor temperature, Time trend, Penetration of Central Heating, Efficiency Policy	Panel Data	-0.16		N/A

[a] C, coal; E, electricity; P, petrol; G, natural gas.
[b] SFD, Single-Family Dwelling; MFD, Multi-Family Dwelling.
[C] ECM, Error Correction Model; [D] ARDL, Autoregressive Distributed Lag; [E]N/A, Not Applicable

The top-down modelling carried out for this thesis (Papers II, III, and IV) uses econometrics to model the main parameters that influence energy demand for space and water heating at a national or EU level. The explanatory variables chosen are: price; income; heating degree days, as a proxy for the effects of the weather; the lag of energy demand, as a proxy for inertia and delayed response to the other variables; and a time trend, as a proxy for linear technical progress. As such, this represents the application of econometric methodology to the engineering world of space and water heating. The main utility of this approach is in facilitating fiscal policy development, since the heating degree days, the lag of energy demand, and the linear time trends are essentially control variables that allow for better estimations of the influences of price and income.

2.3 Data used in modelling energy demand in buildings

Both the bottom-up and top-down modelling approaches require data. In fact, data availability often determines the geographic and temporal scope of the modelling that can be undertaken. Data are also necessary to build indicators that focus on the evolution of heating energy demand, building floor area, and energy prices. An extensive review of the various pan-European data sources carried out before the commencement of this thesis (Ó Broin, 2007) revealed that pan-European energy data categorised by end-use and available in time series are only available from two sources: 1) the Odyssee Database, which contains data from 1980 to 2012; and 2) a database compiled by the late Lee Schipper at the University of California, Berkley, (Schipper, 2010), which contains data from 1970 to 1995. Data are also available from national statistics agencies. However, for studies that compare countries, it is desirable that the data come from the same source, e.g., a database with a pan-European scope, so as to ensure that the variables are defined and measured in the same way.

A drawback associated with the data in the Odyssee Database is that the sources of the data are not explicitly listed. This has led to some concerns regarding the verifiability or quality of the data. The data have been deposited in the database by member organisations in each of the EU-27 countries, although the sources or methods of collection are not defined. Notwithstanding these concerns, this database is unique in terms of the level of end-use and the time series data that it provides. The results obtained with the data used in the present work, e.g., for price elasticities, are comparable to those obtained in similar studies [for example, (Nässén et al., 2008) and (Haas and Schipper, 1998)] using national datasets, thus lending greater authenticity to the Odyssee Database.

The GAINS Model Database (IIASA, 2010) has also categorised energy demand in buildings according to the various end-uses. This has been done for Year 2005 and for a scenario up to Year 2030, based on the Primes official EU baseline (Capros et al., 2008). Data for energy prices for four energy carriers (coal, electricity, natural gas and oil) from 1978 are available from the IEA (IEA, 2012), while historical data on personal income and the consumer price index are available from the OECD (OECD, 2008). It is also interesting to note that the IEA in 2011 recommended action on energy efficiency data collection and indicators as an important area for promoting more informed energy efficiency policy decisions (IEA, 2011). More recently the EPISCOPE and TABULA projects (Episcope, 2016), have been set up which include establishing a database of building typologies across the EU.

The fact that end-use data on demand for space heating are available allows specific focus on this energy service. Figure 1 shows the proportions of space heating used relative to energy for the other energy services. To date, most of the studies of energy use in buildings have examined electricity use or total energy use, despite space heating being dominant. This is mostly because data on space heating have been difficult to obtain. For Papers II–IV of this thesis, either space and water heating or only space heating was examined. This focus on these end-uses makes the work unique in many respects.

2.4 Modelling and methods undertaken for this thesis

In the first study (Paper I), the bottom-up building stock model described by Eq. (2) is applied to estimate the potential role of energy efficiency in the EU Building Stock between 2005 and 2050. The work encompasses both residential and non-residential sector buildings, i.e., the entire stock of buildings across the EU-27. This work highlights the levels and types of efficiency improvements needed to meet EU political goals, and also gives an overview of the energy demand profile of EU buildings.

In Paper II, bottom-up and top-down methodologies are combined. The bottom-up model is that described by Eq. (4), while the top-down model is similar to Eq. (9). The scope of the study is space and water heating in the residential sector of Sweden, and various scenarios of energy demand are examined up to Year 2030. Scenarios for energy prices to Year 2030 are used as inputs to the respective top-down and bottom-up models as part of the estimation of energy savings potential to that date. The rationale for combining methodologies is to highlight *ex ante* the difference between the bottom-up and top-down estimates of the savings potential, the reasons for the different results, and what policymakers can learn from them. The paper is a contribution to the discourse on the Energy Efficiency Gap, as the differences in the estimates made with the two models are assumed to indicate one approach to quantification of the gap.

In Paper III, a time series of the historical data from 1970 to 2005 is analysed using econometric modelling to establish a relationship between energy prices, efficiency, and demand. The scope of the work is space and water heating in the residential sector of four EU countries (France, Italy, Sweden and the UK). The relationship between energy prices, efficiency, and demand is established using a model similar to Eq. (9), and the parameters estimated are then combined with scenarios for energy prices and income to generate various scenarios of energy demand to Year 2050. The work highlights the role and potential of increasing energy prices and general energy policy to date in the EU.

In Paper IV, top-down historical data from 1990 to 2010 are analysed using econometric modelling to establish a relationship between energy demand and the efficiency policy portfolio in place. This model is a variety of the panel data model described in Section 2.2. The focus is on space heating for the residential sector buildings of the EU-15. This work highlights the types of policies that have been most successful at improving efficiency in Western Europe.

3. RESEARCH QUESTIONS AND RESULTS

The goals of the four studies that make up this thesis (listed in Table 1) are to gain insights into and highlight those parameters that can be of use for forming policy and to provide inputs to supply-side models. The boundaries of these studies are generally the energy used and converted in buildings of the EU; neither energy used in other sectors nor energy production (e.g., in power stations) is examined. However, in Paper I, the consequences of energy demand in buildings for CO_2 emissions from the power sector are also included.

As mentioned previously, the undertaken research had as its start-point the task of generating various scenarios for the energy demand in buildings to Year 2050 for the Pathways Program. The program defined three scenarios as the basis of its assumptions regarding the future European Energy System: a baseline, a market, and a policy scenario. The Baseline Scenario, as applied to energy use in buildings, assumed that improvements in energy efficiency ceased after Year 2005. The Market Scenario assumed that efficiency improvements continued at the historical rate, while at the same time fiscal measures, such as a carbon tax, allowed the Energy and Climate policy goals to be met. The Policy Scenario assumed that efficiency improved substantially to meet EU energy and climate policy goals. These three scenarios are used in Paper I of this thesis.

The research proceeded along the following lines. After the completion of Paper I, which was a bottom-up study that was based on scenarios with different levels of efficiency improvement in EU buildings, it was decided to introduce a top-down model for the work of Paper II, to obtain an alternative perspective and a different set of results from that obtained with the bottom-up model. This approach could be used to measure and discuss the so-called Energy Efficiency Gap. To allow this methodology to characterise the energy efficiency gap, the work was restricted to the case of space heating use in the Swedish residential sector. Paper III was designed to examine the role of energy prices in more detail. The work used the top-down approach of establishing prices and other elasticities based on historical time-series data, with subsequent estimations of future demand based on various scenarios for energy prices. Due to data constraints, this work was restricted to the residential sector of four EU countries: France, Italy, Sweden, and the UK. Finally, Paper IV analysed empirically which type of efficiency-based legislation has led to the most significant energy savings in the EU residential sector.

3.1 PAPER I: The effect of improved efficiency on energy savings in EU-27 buildings

This paper presents a classic building stock bottom-up model approach to estimating the energy savings potential of buildings. The method models energy demand in buildings according to Eq. (2), as well as other equations that are described in the paper. The aim of the work was to provide a transparent description of a model that could be applied to calculating energy-saving potentials from efficiency improvements in buildings on a national scale. The rationale for focussing on efficiency was to calculate the levels of energy efficiency that are needed in existing and new buildings to meet EU energy-saving goals. The results obtained provide insights into the general roles of different categories of efficiency, which can be valuable for formulating policy or highlighting areas that merit further research. In addition, Paper I examines the influences of efficiency on primary energy demand, future energy carrier mixes, and CO_2 emission levels.

During the work, a number of different scenarios of demand to Year 2050 were introduced that match those used in the aforementioned Pathways Project, e.g. the Baseline, Market, and Policy. These demand scenarios are used as inputs to the Pathways Program supply-side model, i.e., if one knows what the demand will be one can dimension the supply-side capacity correctly. Implementing the three Pathways Project scenarios involved making assumptions related to the development of energy efficiency and standard of living in the residential and service sectors of each country examined. This explicitly separated the influences of technical and non-technical parameters, in line with the aims of the thesis. Three types of efficiency were analysed, namely the conversion efficiency of boilers, building standards for new buildings, and the end-use efficiencies of appliances and building insulation. The key differences between the scenarios are the assumptions made for these three categories of energy efficiency measures (see Table 3). The modelling was undertaken for the six largest EU countries by population (France, Germany, Italy, Poland, Spain, and the UK), as well as Ireland, Sweden, and a hypothetical entity that represents the remainder of the EU-27.

Table 3 outlines the assumptions used to build the three scenarios used in the work. Rows 5 to 9 of Table 3 give the actual assumptions in relation to efficiency made in Paper I. For example, the efficiency improvements of electricity use in existing residential sector buildings improve by 0.5% per year in the Market Scenario but by more than 2% in the Policy Scenario. Rows 3 and 4 of Table 3 show the increases in the use of energy services related to increases in the standard of living.

Given that the aim was to cover all the buildings in the EU, the model represents the stock at a high level of aggregation with respect to the application of bottom-up modelling, in that no archetype dwellings or individual technical measures are examined (See Section 2 on Bottom-up modelling). Thus, although the approach is bottom-up, the work does not use a rich technological description of the building stock and merely categorises demand into old and new single-family houses, multi-family houses, and commercial buildings. In addition, there is no economic component to the model. Thus, the influences of energy price dynamics are endogenous in terms of the efficiency improvement rates, and income change is endogenous in the standard increase parameter. Nevertheless, the extent of aggregation applied is considered reasonable given the geographical scope of the work.

Table 3 : Model parameter inputs for the three different scenarios applied in Paper I (Table 1 in Paper I).

	Parameter	Baseline Scenario	Market Scenario	Policy Scenario	Source
1	**Construction rate (*C*)**	Same for all scenarios. 0.92%/yr for dwellings and 1.2%/yr for service buildings.			(IIASA, 2010)
2	**Demolition rate (*D*)**	Same for all scenarios. 0.14%/yr for all buildings.			(IIASA, 2010)
3	**Standard increase: Space heating, water heating and cooking (*S*)**	Same for all scenarios. Dwellings, existing, 0.4%/yr; service buildings, existing, 0.39%/yr. Essentially the same for new houses built in the period 2005–2050.			(IIASA, 2010)
4	**Standard increase: Electricity (*S*)**	Same for all scenarios. Dwellings, existing, 1.2%/yr; service buildings, existing, 1.12%/yr in existing stock. Essentially the same for new houses built in the period 2005–2050.			(IIASA, 2010)
5	**Efficiency improvements: Space heating, water heating, and cooking (*F1*)**	No further efficiency measures after Year 2005 in existing stock. No further measures in new houses after they are built.	Dwellings: existing, 0.71%/yr; new, 0.63%/yr. Service buildings: existing, 0.78%/yr; new, 0.64%/yr.	Dwellings: existing, 2.22%/yr; new, 2.68%/yr. Service buildings: existing, 2.16%/yr; new, 2.15%/yr.	(IIASA, 2010) for Market Scenario.
6	**Efficiency improvements: Electricity (*F1*)**		Dwellings: existing, 0.50%/yr; new, 0.50%/yr. Service buildings: existing, 0.65%/yr; new 0.56%/yr.	Dwellings: existing 2.10%/yr; new, 1.98%/yr. Service buildings: existing, 2.23%/yr; new 2.52%/yr.	(IIASA, 2010) for Market Scenario.
7	**Specific space and water heating energy use in new buildings (*NUC*)**	Same as for Year 2005. Average for EU is approximately 100 kWh/m^2/yr for space and water heating	Same as for Year 2005. Average for EU is approximately 100 kWh/m^2/yr for space and water heating.	Approximately 40 kWh/m^2/yr in Year 2020. The same level is assumed after Year 2020.	(Jagemar, 2010)
8	**Specific electricity use in new buildings (*NUC*)**	Same as for Year 2005.	Same as for Year 2005.	Average of 23 kWh/m^2/yr for dwellings, and average of 64 kWh/m^2/yr for service buildings.	(IIASA, 2010)
9	**Conversion Efficiencies (%)**	Same as for Year 2005	Same as for Year 2005	Improve from or stay static: Oil 0.71 to 0.85, Coal 0.7, Gas 0.7 to 0.9, Biomass 0.6 to 0.85, DH, 0.95 and Electricity 0.99 to 2.0	Assumptions
10	**Energy Carrier Mix to 2050**	Based on trend in period 1990–2005	Progressing to: Gas, 8%; DH, 30%; Electricity, 50%; Biomass, 11%.	Progressing to: Gas, 8%; DH, 20%; Electricity, 40%; Biomass, 31%.	Assumptions
11	**Final to Primary Factor**	Oil, Coal, Gas, Biomass = 1; DH = 1.27; Electricity = 2.60 in Baseline, 2.30 in Market, and 2.34 in Policy Scenarios.			(Unger et al., 2011), (Werner, 2006), (Moomaw et al., 2011)
12	**CO$_2$ Intensities (kg/MWh)**	Oil, 274; Coal, 342; Gas, 202.			(Unger et al., 2011)
		DH, 255; Electricity, 414; Biomass, 0.	Progressing to: DH, 2; Electricity, 10; Biomass, 0.	Progressing to: DH, 42; Electricity, 20; Biomass, 0.	(Unger et al., 2011)

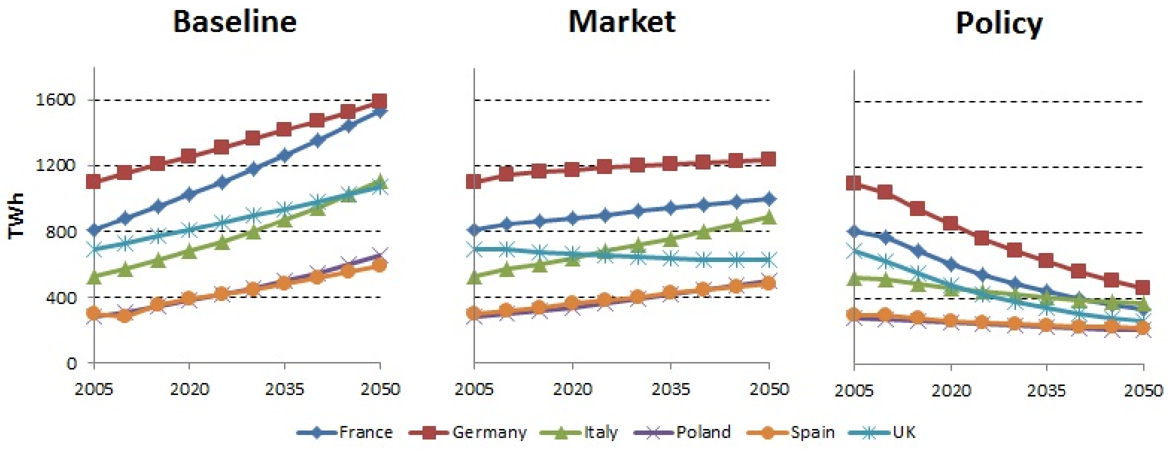

Figure 5 : Development of final energy demand from Year 2005 to 2050 for the building stock of the six largest EU countries (by population), as obtained for the three different scenarios from the modelling developed in Paper I. (Paper I, Figure 3).

Figure 5 shows the results obtained for final energy demand in the three scenarios for the six largest EU countries. In the Baseline Scenario, efficiency improvement stops after Year 2005, resulting in 'runaway' growth in energy demand with, for example, a doubling of energy demand in France over the period. In the Market Scenario, where efficiency improves at the historical rate, energy demand stabilises. In the Policy Scenario, where end-use efficiency improves by 2% per annum, substantial reductions in demand (over 100% in some cases) are observed throughout the time period.

The major findings from Paper I that should be of interest to policymakers are that:

- The implementation of efficiency legislation at the historical rate is necessary to avoid runaway growth in demand caused by larger floor areas, more appliances, and general income-related parameters;
- Efficiency improvements that concern end-uses, conversion, and new buildings all contribute to lowering final energy demand. Therefore, policymakers should focus on a combination of minimum efficiency construction standards, improved conversion efficiency standards for final energy to useful energy, and a minimum 2% annual improvement in end-use efficiency applied at the useful energy level;
- Demand for hot water and electricity for appliances may increase moderately, while the total final energy demand in buildings will fall, as seen for the Policy Scenario.

The Policy Scenario of Paper I offers a panacea for EU policymakers because it shows that living standards can be maintained while simultaneously lowering energy demand. For this to happen, however, there must be an approximately 2% annual improvement in efficiency. While technically feasible, such levels of efficiency improvement have not been achieved previously. The reduction in demand between the Baseline and the Market scenarios shows the contribution that efficiency improvement can make if efficiency improvements continue at the historical level. Thus, acceleration of the roll out of efficiency technologies would be necessary to bring the Policy Scenario to fruition. The reasons put forward for why efficiency has not improved to a greater extent historically include the idea that the necessary political will has been compromised by vested interests (e.g., electricity utilities) and the notion that too many efficiency improvements reduce welfare (Jaffe et al., 2004). The reasoning behind the lack of further implementation of energy efficiency is discussed further in Section 3.4.

3.2 PAPER II: Quantification of the energy efficiency gap in the Swedish residential sector

Paper II uses a more detailed bottom-up model than that used in Paper I and introduces top-down econometric modelling to the work. From the results obtained in Paper I, two questions arose: 1) Would the results be different if the costs of the technologies were included?; and 2) What would the outcomes be if energy demand was related to price and other elasticities calculated from historical data? To address the first question, the ECCABS stock model [described by Eq. (4) above] was used to quantify the full cost of the effective energy savings potential (in effect, the items presented on the left-hand side of Figure 6, as discussed in the section on energy pricing below). The second question was addressed by applying a top-down econometric model [described by Eq. (9) above] to the same case to which the bottom-up model was applied. The rationale here was that the inertia related to the take-up of energy efficiency measures in the building stock could be captured by the top-down model. In doing so, the top-down model could present an estimation of the level of energy savings potentials in the building stock, assuming that past trends for the implementation of efficiency measures continued. In contrast, the bottom-up modelling does not provide any prediction but can quantify the full cost of the effective energy savings potential, typically using social discount rates. For it to be applicable for predictive purposes, an implicit discount rate (as opposed to a social discount rate) would need to be utilized in the bottom-up model to reflect the transaction costs and the risk perceived by householders. Both models were applied to the case of useful energy demand for space and water heating to Year 2030 in the stock of the residential sector buildings in Sweden that existed in Year 2005. This parsimonious case was chosen because it was already familiar to the researchers, as well as to focus on the methodological aspects of the work. Moreover, this case choice was in line with Summerfield and Lowe's (2012) call for buildings-related research that targets specific questions '*e.g., the energy demand in the existing building stock in developed nations*'. In summary, the aim of Paper II was to explore what could be gained from performing bottom-up and top-down analyses of the same energy system.

The discrepancies between the outcomes from the bottom-up and top-down model would also constitute one quantification of the so-called 'Energy Efficiency Gap'. The seminal work on the Energy Efficiency Gap conducted by (Jaffe and Stavins, 1994) defines it as being the difference between the optimum level of savings that would maximise welfare and the actual level of savings achieved by householders. Another definition, provided by (Persson et al., 2009), is that the gap represents the difference between the techno-economical potential energy savings in the stock of buildings and the savings that are realised. The (Jaffe and

Stavins, 1994) definition places the discourse around the gap between what an engineer and an economist would separately calculate as the energy savings potential. In the view of the economist, the implementation of the full cost-effective efficiency potential could actually reduce overall welfare, as it ignores consumer preferences for other welfare-enhancing options. For the work in Paper II, the definition of Persson and colleagues is used, i.e., welfare economics are not considered as they are beyond the scope of the work. The difference in the results obtained from the two models was considered to be equivalent to the *ex ante* Energy Efficiency Gap, as it estimates *ex ante* the difference between what is technically and economically possible with what is likely to happen assuming the continuation of past trends. The methodology also allows analysis of the values of two parameters that are key to the respective models: the discount rate in the bottom-up model; and the time trend in the top-down model.

Two energy price scenarios, a high-price and a low-price scenario, are used as inputs to the respective models. These price scenarios were constructed by adding assumptions related to the levels of VAT, distribution charges, excise, energy and carbon taxes to the IEA scenarios for fossil fuel prices to Year 2030 (IEA, 2009). The assumptions were identical for both scenarios, apart from the carbon tax for which there was a high level and a low level.

In line with *a priori* expectations, the cost-effective energy savings potential uncovered by the bottom-up model is higher than that found with the top-down model. In comparison to the level of energy use in Year 2005 (74 TWh), the top-down model predicts for Year 2030 reductions in demand for the high-price and low-price scenarios of 17 TWh and 21 TWh, respectively. The bottom-up model predicts corresponding reductions in demand of 25 TWh and 31 TWh. Thus, there is an energy efficiency gap of at least 8 TWh in Year 2030.

The following findings should be of interest to policymakers:

- An implicit discount rate of 10% would render the results from the bottom-up modelling identical to those obtained from the top-down modelling. This implies the existence of a ‘discount gap’ of 6% between the social discount rate and the implicit rate applied by households.

- The top-down model shows that non-price effects reduce demand by around 0.5% per year. Assuming that non-price effects doubled to around 1%, the results from the top-down model would be identical to those obtained from the bottom-up modelling. This suggests that the combined effort of the annual implementation of legislation that supports efficiency through, for example, support schemes and regulations needs to be doubled to close the energy efficiency gap.

- While higher prices (as represented by the high-price scenario) for energy may achieve a global carbon target (e.g. 450ppm) or cover the requirements of a Pigovian tax to reduce greenhouse gas emissions, at the residential sector level in Sweden they are not so effective in reducing energy demand or CO_2 emissions. This is because the price elasticity has been found to be low but also because the energy carrier mix used for Swedish Residential Sector heating is already nearly decarbonized.

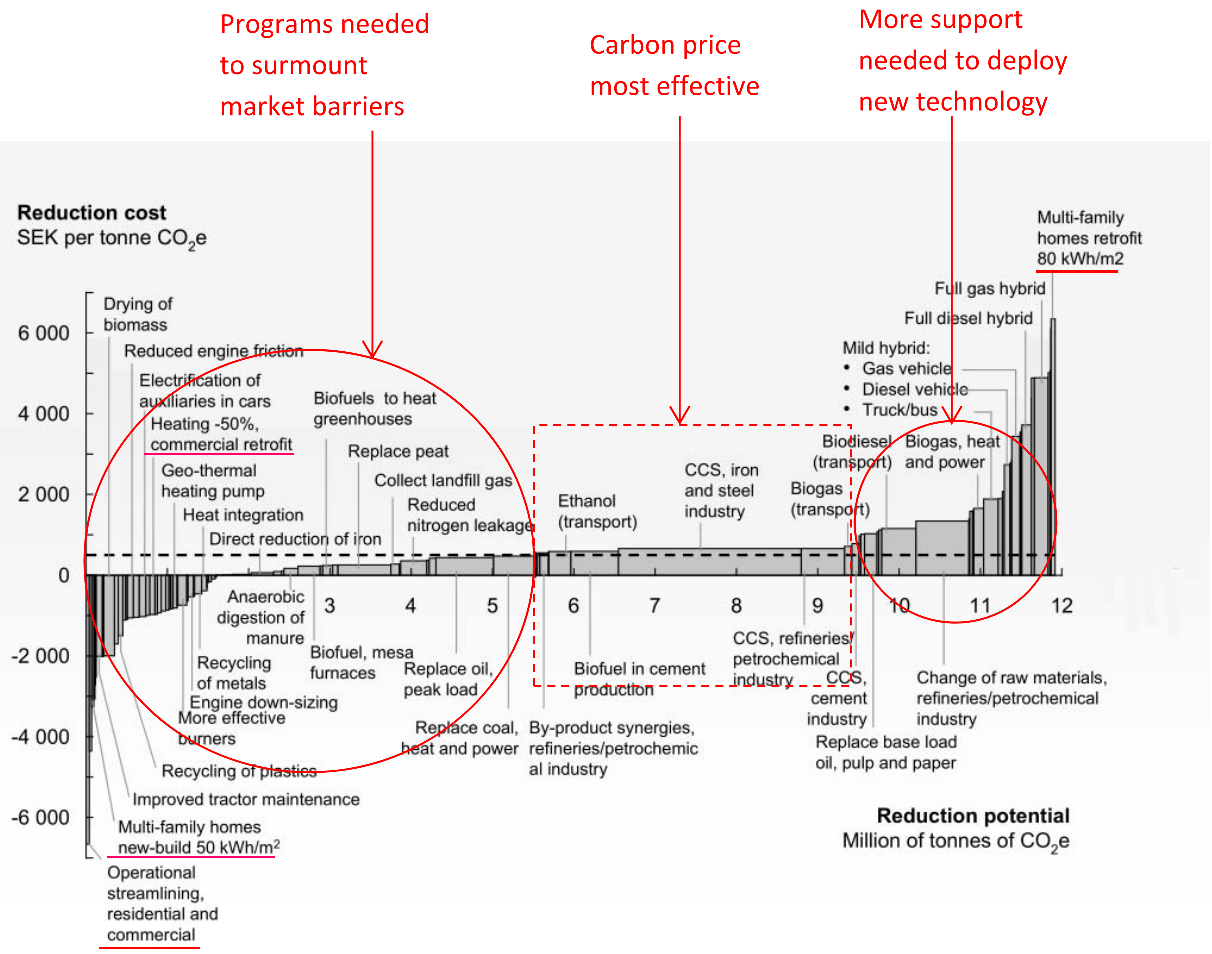

Figure 6 : MAC curve for Sweden. Measures designed to reduce energy demand in buildings are underlined (McKinsey, 2008).

The Marginal Abatement Cost (MAC) curve for Sweden shown in Figure 6 (McKinsey, 2008) offers another perspective on the results from Paper II. Although Paper II does not focus on CO_2 abatement, Figure 6 is nonetheless useful for discussion purposes because: a) it includes energy efficiency measures; b) the principle of its operation, i.e., reducing CO_2, can also be applied to reducing energy demand; and c) the costs calculated for the measures shown are the results from bottom-up modelling. The first category on the left-hand side of Figure 6 shows measures that are already profitable to implement. In other words, the return on the investment in these measures in terms of energy saved would be greater than the investment itself (assuming a certain interest rate on the investments made). The second category of measures, in the middle of Figure 6, would be profitable at CO_2 prices of 500 SEK (approx. €55) per tonne, while the measures on the right-hand side of Figure 6 would require substantially higher CO_2 prices and supplementary policy measures to be implemented. Although the measures listed on the left-hand side of the figure should be feasible at current or even reduced carbon prices (as dictated by the bottom-up modelling), in general that has not happened[8]. This is due to market barriers that prevent responses to the price signal (Cowart, 2011). There is extensive literature detailing these market barriers, which include access to information, high up-front cost problems, consumers' high discount rates, un-priced externalities, split-incentives, and others (Cowart, 2011). Once these market barriers are taken into consideration, the cost of CO_2 abatement increases and as such the profitable carbon reduction potential decreases.

The difference between the bottom-up estimate shown in Figure 6 and an estimate that additionally incorporates market barriers is an estimation of the Energy Efficiency Gap. Thus, to realise fully the least cost potential shown in Figure 6 in light of the known market barriers and imperfections, carbon pricing obviously needs to be augmented by supplementary policies, as carbon pricing *per se* is not sufficiently potent to make things happen. In other words, higher prices alone cannot close the gap. The finding in Paper II that the combined effort of the implementation of efficiency policy must be doubled to reach the bottom-up potential reflects the limitations of the price effect. According to (Ryan et al., 2011), the two supplementary non-price measures that should form the "core" policy set are: 1) cost-effective energy efficiency policies to unlock abatement potential that is otherwise untapped by the carbon price signal; and 2) research, development and demonstration (RD&D) and technology deployment policies to bring forward new mitigation options. The first supplementary measure can be seen as targeting the measures on the left-hand side of Figure 6, while the second can be seen as targeting the measures on the right-hand side. If cost-effective energy efficiency opportunities are not exploited, a higher price for carbon (or energy) is needed to deliver the same level of emissions reductions, increasing the cost of the policy response, i.e., the higher carbon price activates more of the mitigation measures on the right-hand side of Figure 6, whereas it has no impact on the cost-effective options on the left-hand side, which are in a sense locked behind market barriers, such as reducing heating energy demand by 50% in commercial buildings through retrofitting. Thus, to achieve the bottom-up potential described in Paper II, the first supplementary measure referred to previously (Ryan et al., 2011) is needed so as to double the level of non-price measures implemented to date.

3.3 PAPER III: The influence of price and non-price effects on demand for heating in the EU residential sector

Paper III examines the impacts of energy prices on demand. Although Paper II suggested that increasing energy prices would have little impact on demand in the Swedish Residential Sector, the question remained as to whether this would be true for other EU countries, especially those that were significantly larger or used large quantities of fossil fuels, e.g., natural gas, for heating. A more detailed exploration of the role of energy prices on demand could simultaneously examine non-price effects, so as to highlight for policymakers the relevant importance of price and non-price effects. The modelling approach chosen was to use a top-down econometric model [similar to Eq. (9)], given that energy prices were the main

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[8] One could speculate that a top-down modelling exercise would estimate higher costs for the same measures. However, top-down modelling does not go into the required technical detail. (Jaccard, 2009) has used the CIMS hybrid model to include some extra costs.

lever of interest. Figure 7 shows the evolution of end-use energy prices from 1970 to 2005 as used in Paper III.

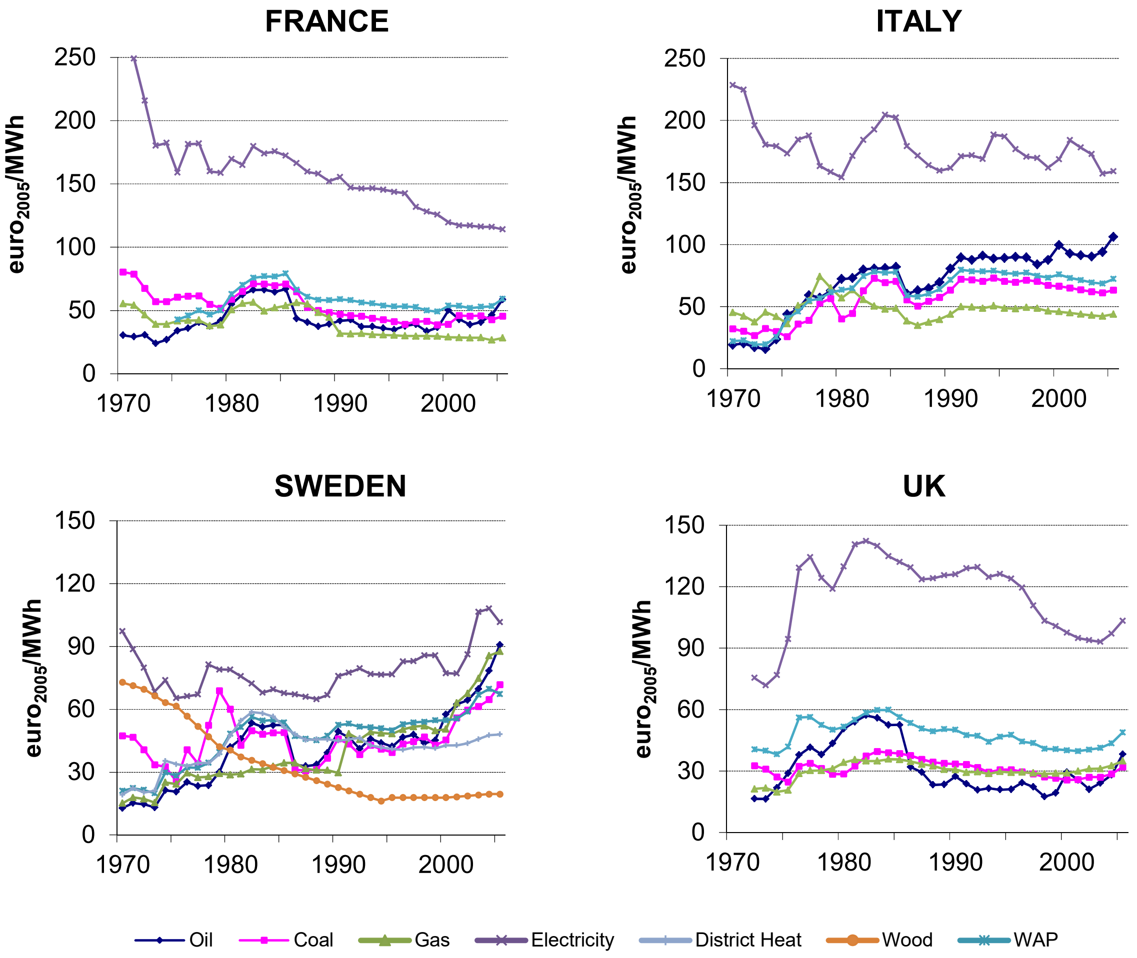

Figure 7 : Time series of prices for energy end-uses for main energy carriers from 1970 to 2005 (Data derived from the Odyssee Indicators (Enerdata, 2013) and Shipper (Schipper, 2010) databases.

To undertake the modelling, energy demand was first disaggregated into activity, structural, and intensity effects (in the same way as Figure 2 shows), to allow these three parameters to be modelled individually. One reason for doing this was that, given the criticism of using top-down modelling to estimate future energy demand (see discussion below), estimating disaggregated levels of physical parameters (such as efficiency) using top-down modelling rather than aggregated sums (such as total energy demand) could provide more plausible estimates of long-term energy demand. Such an approach to modelling demand has been proposed by (Chateau and Lapillonne, 1978) and is used in their MEDEE model. To obtain a robust estimation of price effects, it was desirable to examine data from the 1970’s onwards, to ensure that the effects of the oil crisis were captured in the modelling. The data available for this analysis for the residential sector were only available for four EU countries: France, Italy, Sweden, and Italy. Although the aforementioned Odyssee Database covers more countries, the data that it contains are from 1980 onwards, thereby missing the critical years of oil crisis-related price-spikes in 1974 and 1979. Harmonised data for the 1970’s for the four countries were found in the database compiled by (Schipper, 2010).

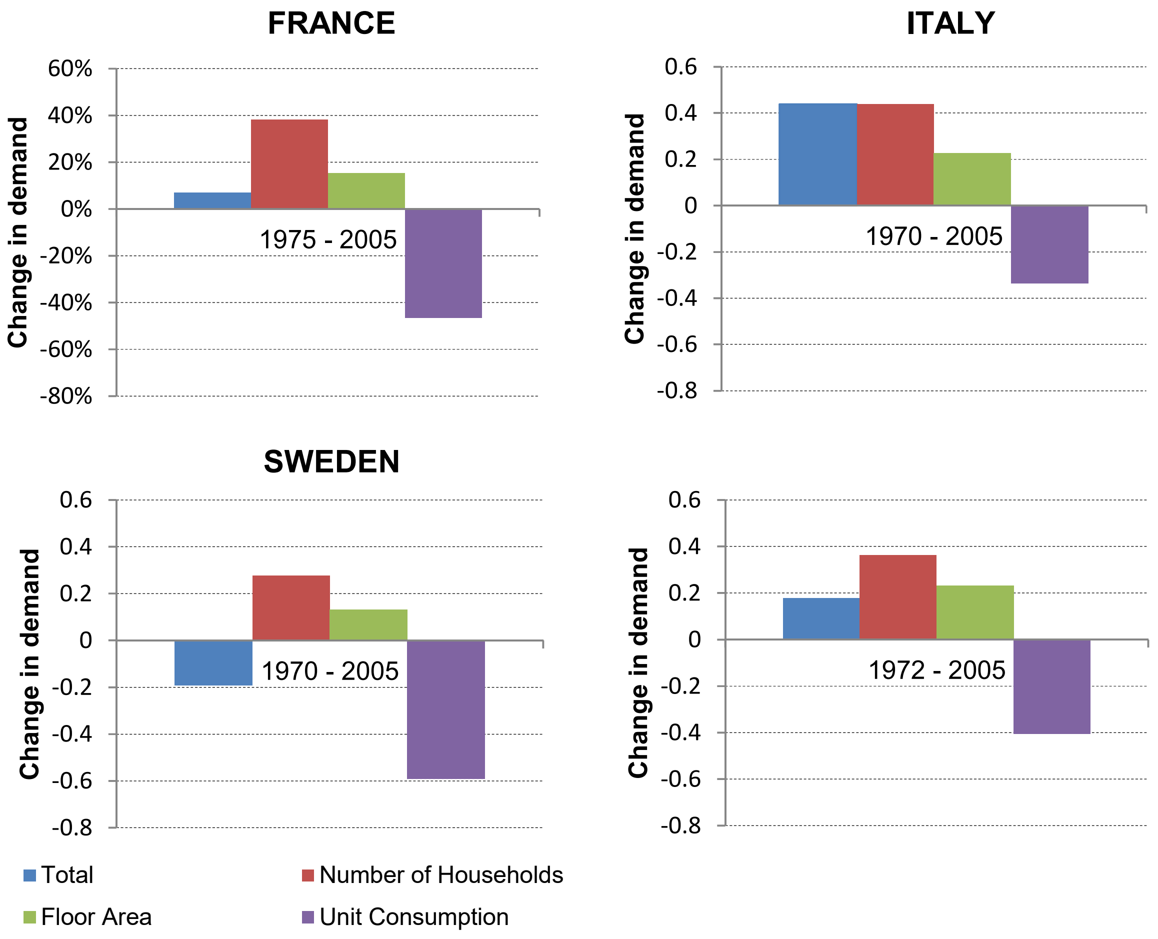

Figure 8 : Index Decomposition of residential sector energy use for space and water for the period 1970–2005 (Paper II, Figure 2).

Figure 8 shows the historical index decomposition of energy demand for heating for the four countries analysed in Paper III. The modelling work carried out for Paper III examines the price and non-price effects on change in unit consumption of energy, as shown in the fourth column of Figure 8, as well as the effects of income on the change in floor area. This produces price elasticities of demand for the change in unit consumption and income elasticities of demand for floor area, as well as a coefficient for the development of non-price effects. Non-price effects are assumed to include efficiency policy and autonomous technical progress. The elasticities and the coefficient of non-price effects [β_5 in Eq. (9)] are combined with three scenarios for prices and one scenario for income to estimate the total energy demand to Year 2050. In contrast to Paper II, where price scenarios were constructed bottom-up, the three price scenarios are simply 0%, 2%, and 3% annual increases in 2005 energy prices, while the income scenario is an approximate 2% annual increase. The justification for this approach to price scenarios is based on an examination of historical energy prices and a brief review of prospective prices for home heating. It can also be said that the exercise carried out in Paper II to build the price scenarios bottom-up provided a range of price scenarios that were similar to what would be obtained by merely increasing the observed base year prices (for Year 2005, shown in Figure 7) by an annual percentage change.

Applying the three price scenarios and one income scenario, the following results were obtained for the four countries:

- For a 0% price increase, there are consistent annual reductions in unit consumption (energy demand per floor area) due to the continued impacts of policies and measures (assuming that the implementation of these continues at the historical rate).

- A 3% energy price increase leads to an approximately 1% decrease in total final energy demand, despite continued increases in population and heated floor area.

- The price elasticities of demand for energy are low. They have been calculated over a time series of 40 years. From a modelling perspective, they can be useful for estimations for an equally long time period.

If one ignores the discourse around constant elasticities (see *Discussion* section below) and the lack of technological descriptiveness of the top-down modelling employed, the policy implications of Paper III are as follows:

- The rate of implementation of efficiency-focused legislation needs to follow historical trends if improvements in efficiency are not to stagnate. This finding reinforces a similar finding from Paper I (see Figure 5), showing that demand would have increased substantially if it were not for the levels of efficiency that have been introduced to date.
- Owing to the low price elasticity, increasing energy prices achieves only small reductions in energy demand and thus, other non-price efficiency-inducing measures are needed to achieve significant reductions in demand, e.g., reductions in demand that met the passive house standard in existing buildings;

The results obtained in Paper III in relation of the effects of raising energy prices can be discussed in a wider research context. Several studies point to diverse effects of increasing prices in different settings. There are consequences for household welfare and the economy from the increases in energy prices and the related impact of increases on income. Another aspect is the role of '*shock-high'* price changes. The rest of this section reviews the evidence for the effects of raised prices and income and relates to the findings in Paper III.

Macroeconomic modelling carried out for the EC Energy Directorate DG TREN (Boonekamp et al., 2011) suggests that if households and industry must spend more of their disposable income on energy due to increased energy prices, they will have less real income to spend on other goods and services, thereby reducing demand and general activity in the economy. The conclusion to be drawn from that work is that this would lead to a lowered demand for goods and services, and thus loss of output and jobs. The authors describe how prices are made up of wholesale energy carrier prices, as well as distribution tariffs, transmission tariffs, supply service margins, and government consumption and carbon taxes, including VAT (Boonekamp et al., 2011). Thus, according to that study (Boonekamp et al., 2011), changes in any of these parameters can lead to the negative macroeconomic consequences described. A further effect of increased prices described by Boonekamp and colleagues is that low-income households might have problems paying for adequate levels of home heating, leading to a so-called ‘energy poverty’ situation.

Energy demand is of course also affected by changes in personal income. (Dulleck and Kaufmann, 2004) reported the long-term income elasticity of domestic demand for electricity in the Republic of Ireland as 0.39, meaning that for a 1% increase in income there should be approximately 0.4% increase in electricity demand. They also showed that the price elasticity of domestic electricity demand is not statistically significant. They posit thus that “... *the insignificance of the price coefficient may be explained by two related factors. Firstly, in developed countries electricity has become a basic need for households so that the price elasticity of electricity demand is small, i.e., big price movements would be required to affect demand patterns significantly. This leads to our second factor, as big price movements have not taken place in the observed period [1976 - 1993] (i.e., electricity price was not the prime policy variable), the price variable is not a determinant of electricity demand.*” Their findings suggest that the outcomes from the macroeconomic modelling exercise described in the previous paragraph, although theoretically possible, have not occurred since at least the 1970’s. This means that for any estimation of future demand, the interplay between rising prices and income is important and that the impact of very high prices should be modelled.

Big price movements have been observed and analysed by (Reiss and White, 2008). They examined the impacts of electricity price increases of >100% that occurred during the California Energy Crisis of 2000 and found that electricity demand fell substantially in response. However, the ‘shock-high’ price increases of >100% led to a storm of public protest and a cap on electricity prices being introduced by the state government. This measure resulted in the demand reverting to its pre-crisis level, although the electricity utilities that had to sell electricity below cost were threatened with insolvency. In response, the state government organised a public appeal to ask the population at large to reduce electricity consumption. This appeal had the desired effect of reducing demand and averting problems for the utilities. However, (Reiss and White, 2008) speculate that if policymakers had not imposed the price cap substantial behavioural changes with regard to energy use could have been achieved. Their main finding in the context of this work is that shock-high prices do cause demand to fall. However, their description of how politicians do not allow such a situation to continue unabated needs to be borne in mind.

(Gately and Huntington, 2002) have reported that in virtually all countries, people adjust their energy usage much more slowly in reaction to changes in energy prices than to changes in their income. (Ryan et al., 2011), in a review of the results from many countries, discovered relatively low energy price elasticity in the buildings sector, suggesting only a weak correlation between energy prices and investments in energy efficiency in buildings. (Boonekamp, 2007) has suggested that in a longer time-frame rising energy prices have the greatest impact on demand when householders have some choice with regard to energy systems and appliances. (Douthitt, 1989) found similar results for Canada, i.e., that households that pay above the average price for energy but that also have choice in relation to the energy commodities they can purchase, display near unity long-term price elasticity of demand. A study carried out for British Gas (CEBR, 2011) has shown that over the period of rising gas prices between 2006 and 2010, householders reacted to price rises by changing to lower-cost retail suppliers rather than reducing their levels of consumption. Thus, they found that domestic natural gas consumption has not been directly influenced by changes in retail gas prices. In contrast, they found that during periods of prosperous economic growth, domestic natural gas consumption increases as expenditure on energy rises.

This brief literature review suggests that the reactions of consumers to increased energy prices evolve in the following order: (i) switching to a lower tariff supplier; (ii) taking conservation measures; (iii) investing in more efficient infrastructure; and (iv) political action. These effects occur to different degrees across social classes depending on income levels. In recent decades, increases in income (See Figure 3) have compensated for any prices increase to the extent that price elasticity has been low, and there have been no perceptible negative effects on the economy. This is confirmed by the empirically established price elasticities presented in Table 2 above, which include the low price elasticities that have been noted for France, Italy, Sweden and the UK in Paper III of this thesis. These low price elasticities can be related to a lack of choice, as Boonekamp suggests, low prices over the long term, as Dulecka & Kaufmann suggest or to the fact that shock-high prices are needed to propagate change. Disaggregating the demand (as shown in Figure 8) also highlights how increasing income can drive consumption, average dwelling size in this case, thereby increasing the area that needs to be heated regardless of price dynamics.

Relating to the results and discussion in Paper II, the low price elasticities also reflect market barriers that are not easily removed by raising prices. While the case described for California seems to have reduced demand significantly, it also seems to have caused undue hardship for householders, as evidenced by their engaging in political action, meaning that underlying market barriers were not necessarily removed in this case, rather the people simply reduced their consumption. In summary, demand needs to be reduced as much as possible *via* efficiency-focused policies and measures in order to ensure the least-cost solution and to reduce the deleterious effects on low-income households of higher energy prices. To achieve this, policies that address infrastructure lock-in and investment barriers may be needed (Ryan et al., 2011).

3.4 PAPER IV: Energy efficiency policies for space heating in EU countries: A panel data analysis for the period 1990–2010

After the exploration of the role of energy prices in Paper III, the question arose as to the precise role of efficiency policy. The discussion in Papers II and III presented above highlight that legislation that encourages the diffusion of efficiency is necessary to overcome market barriers, which increasing prices alone cannot overcome. Thus, it was considered interesting to examine empirically how different types of efficiency policies, e.g., regulations, had succeeded in reducing demand, by representing policy as an explicit variable in a model. In the model used in Paper I, policy implementation is assumed to be part of a variable that represents annual efficiency improvement rates and is introduced exogenously to the model. In the top-down models used in Papers II and III, policy implementation is included in the variables represented by the time trend. In Paper IV, the time trend is included, in addition to the explicit policy variable, but is assumed to represent only autonomous technical development, rather than reductions in demand that come about as a result of legislation. A key feature of the model applied in Paper IV is the method by which efficiency policies have been represented. This is done by the creation of a time-series of data that represents the policy in place for each year.

Similar to Papers II and III, the dependant variable modelled is unit consumption for heating (kWh/m^2/year), although for Paper IV, only space heating is modelled (as opposed to the space and water heating modelled in Papers II and III). Paper IV also sought to extend its geographic scope to as much of the EU as possible, so as to use panel data econometrics to analyse the region as a unit rather than to model individual countries. It was also decided that it would be sufficient to model how efficiency policy had changed demand historically, rather than also using the results obtained to estimate future demand. The energy price time-series used is a WAP for space heating, similar to that used in Papers II and III.

In Paper IV, it is shown that regulatory policy has had a greater impact on energy demand across western European countries than informative policies or financial subsidies. This finding applies to policies in place between 1990 and 2010. It could be argued that for a future regime that focuses more explicitly on unlocking the savings potential outlined on the left-hand side of Figure 6 that this may not be the case, i.e., that informative policies, such as the EPBD, may have more of an impact. Nevertheless, the take-home message for policymakers from Paper IV is that:

- More regulation is necessary across the board if EU-wide energy goals are to be met expeditiously.

This finding regarding the success to date of regulations can perhaps be explained by what (Jakob, 2007) describes in his PhD thesis, that building codes for new buildings promote the use of similar energy efficiency technologies *via* a spill-over effect on the renovation of existing buildings. This makes building codes and standards *technology push*-type policy measures.

Policymaking, such as that for efficiency, occurs within a political framework in which economic growth and employment are usually paramount. This means that policy ideas aimed at reducing energy demand usually have to pass a political ‘feasibility test’, which requires that they do not jeopardise economic growth or employment levels. Even when policy ideas pass this test it can happen that there are features of the *status quo*, e.g., subsidised energy prices or employment in fossil fuels, that are judged to be more expedient to maintain rather than reducing greenhouse gas emissions. In the EU, for example, some argue that excessive taxation of greenhouse gas emissions would lead to a flight of industry to regions with a less draconian greenhouse gas reduction regime. Diverse groups of stakeholders, such as those representing heavy industry, electricity utilities, renewable energy, environmental groups, trade unions, and consumer organisations, have different standpoints, all of which are taken into consideration by decision-makers. For example, some of these stakeholders argue that expansion of electricity production from nuclear fuel is positive because it is not carbon-based, while others argue that the risk of an accident associated with nuclear energy is too great as compared to the benefits.

As power production from fossil fuels happens at a relatively low number (hundreds) of power stations (known in research jargon as 'large-point emitters'), it is easy to map their emissions and target them through a carbon reduction policy regime. However, the nature of their concentration also means that this sector is financially well-endowed and has significant political clout, which they can apply to reduce the ambition of energy policies that would affect their business. Therefore, if policymakers 'back-off' from measures that are focused on large-point emitters they can still focus on subsidising non-carbon electricity production or reducing the demand for energy. Obviously, such measures have implications (albeit less direct ones) for the concentrated power sector. In terms of reducing energy demand, improved efficiency is the main policy goal. Studies have shown that improved efficiency is profitable, has few if any drawbacks for the economy, and does not seriously threaten the *status quo*. However, since efficiency policy in the residential sector (for example) must occur at the household level, it is being applied to a very heterogeneous population that runs into hundreds of millions. This is quite different from the technical nature and low number of large-point emitters. The title of a paper published by (Janda, 2011), '*Buildings don't use energy, people do*', sums up the general issue with applying efficiency measures across the stock of buildings at large, in that the heterogeneous values, needs, and knowledge of the population at large make the diffusion of efficiency very difficult. These issues also contribute to the energy efficiency gap, as discussed in Paper II.

Notwithstanding the finding of Paper IV that regulatory policy has been better than financial or informative policy in reducing demand between 1990 and 2010, regulations have not been embraced in the EU to the extent that one might expect or desire. This applies in particular to building standards that could reduce significantly the energy demand for space heating. Space heating is particularly important because it accounts for >60% of energy use in European buildings (See Figure 1). Certain EU Member States have opposed EU-wide mandatory building energy performance standards (Boasson and Dupont, 2015), which were proposed during the negotiations around the Energy Efficiency Directive (EED). Instead, a compromise has been agreed whereby EU Member States must decide on their own mandatory building performance standards. Ultimately, certain stakeholders have made the case for not introducing EU-wide efficiency standards for buildings based on how it is perceived they would affect the economy or jobs. Another way in which this situation is manifested is that the main tool for fostering efficiency in the EU legislation on efficiency in buildings is that a label stating a buildings energy performance be displayed in a public place. Laudable and all as this effort is, it amounts to an information campaign, which it is hoped will lead to market transformation. Market transformation in this sense means that home buyers would chose more efficient dwellings based on the new information provided in the label. Based on the empirical results presented in Paper IV, such an information-led market transformation is less likely to work than a regulation-based one. In this context, it seems apt to quote the climate economist William Nordhaus: ‘If a politician’s proposal does not raise the price of carbon, you should conclude it’s not serious’(Jaccard, 2013). A regulatory measure has been proposed as part of the aspect of the EED that requires ‘nearly zero energy buildings (nZEB)’ for newly built buildings by Year 2020. However, as the construction rate in Europe is low, it may take a long time for this measure to have a significant impact given that it does not affect the existing building stock. In addition, the Entranze EU Project (Kranzl et al., 2014) has recently shown that most EU Member States equate nZEB with the current cost-optimal efficiency solution found for their respective building stocks, meaning that the impact of the nZEB requirement in the EPBD is reduced significantly and does not present a breakthrough for more ambitious standards for new buildings. It is of course possible that the spill-over effect mentioned above could result in the nZEB requirement having some impact on the existing building stock. As of summer 2015, the EC Commissioner for the Energy Union, Maroš Šefčovič, is proposing stricter energy efficiency and performance laws to be enacted in 2016 because the savings envisaged in the EED have not happened and furthermore because all EU countries except Malta have failed to implement the directive fully (the EED was published in 2012) (Euractiv, 2015).

4. Discussion

This thesis, which consists of this introductory essay and the four appended original papers, uses both top-down and bottom-up modelling methods to analyse in detail energy demand in the EU Building Stock. The aim of the work was to gain insights into key technical and non-technical parameters that could facilitate energy policy formation. Outputs from the modelling also provide demand scenarios, which are used in supply-side models. The methods applied have been described in detail in Section 2 and the results obtained are given in Section 3. This section presents a general discussion of the advantages and disadvantages of using top-down and bottom-up energy system models and deals with some of the issues related to the models used in this thesis. The motivation for including a critique is that of (Summerfield and Lowe, 2012), who have highlighted the need for modellers to '*communicate the limitations of their models to their clients*'.

Top-down models applied to the residential sector provide an estimation of the historical importance of system-level parameters, such as energy prices, personal income, the climate, and levels of efficiency, with respect to energy demand. These parameters can be used to estimate future energy demand if one assumes that there are no changes in the relationships that they describe. In contrast, bottom-up models can estimate the types of technologies needed to achieve an energy reduction. This is how top-down and bottom-up models have been applied in Papers I to IV of this thesis. Individually or in combination they can also be used in policy formulation, e.g., to define reasonable efficiency improvement goals.

For the residential sector, (Swan and Ugursal, 2009) have given a synopsis of the different benefits of top-down and bottom-up modelling systems. They start by pointing out that as the residential sector is usually quite stable in terms of its development, with a construction rate of about 1% per annum, widespread electrification and the penetration of central heating have already occurred. In addition, it has good predictive capability for small deviations from the *status quo* and thus it is reasonable to estimate future demand in this sector based on past trends (*as a top-down model does*). Swan and Ugursal qualify their framework by stating that top-down models are found wanting when there are paradigm shifts caused by technological breakthrough or supply change or even changed weather patterns. In other words, top-down modelling expresses its main benefits when there are no large discontinuities. In summarising their ideas, (Swan and Ugursal, 2009) state that in the current period of rapid technological development in the sector, expedited not least by climate and energy policies and limitations of the energy supply, bottom-up models are better at modelling the technologies needed to achieve a low-carbon future.

In writing about the general trade-offs between top-down and bottom-up modelling systems, (Mundaca et al., 2010) concur with (Swan and Ugursal, 2009) and write that the statistically derived relationships embedded in historical data used by modelling studies are precisely those that modelled policy instruments aim to change. They conclude that the explicit or implicit assumption that market and behavioural failures are considered in the historical data, or in an implicit discount rate, seems to be part of the policy evaluation challenge itself. This point refers to the inertia of technical change, which top-down models capture but which may be caused by market barriers that enhanced efficiency policies could target. (Kavgic et al., 2010) also concur with these groups when they write that the reliance on past energy–economy interactions (*of top-down models*) might also be inappropriate when dealing with climate change issues where the environmental, social, and economic conditions are entirely different to those previously experienced. (Koomey, 2000) uses the phrase “The Big Mistake” to describe the heavy reliance on statistically derived historical parameters for modelling, and proposes that creating a world with vastly lower carbon emissions presupposes massive behavioural and institutional changes, which render past relationships between energy use and economic activity largely irrelevant (just like after 1973). Thus, to summarise the above arguments, top-down models have no inherent capability to model discontinuous changes in technology.

While the above arguments do not critique top-down modelling *per se*, others have questioned the basic mechanics of top-down models (Nakata et al., 2011; Sterman, 1991), in stating that the key parameters of top-down models (*price elasticities*), although derived from historical time-series data, may not be be valid into the future. The price elasticities presented in Table 2, which are generally low, should be examined in this regard, i.e., if it is possible that they are too low to be sufficiently reliable for use in modelling of future energy demand. (Sanstad and Greening, 1998) have postulated that econometric models are probably only good representations of economic conditions 5–10 years into the future, assuming that current economic conditions continue uninterrupted. There is a subtle difference between these latter two arguments and those presented in the previous paragraph. The former argue that bottom-up models are more appropriate given the need for ‘discontinuities’ and ‘regime changes’ to move society towards a low-carbon future, while the latter state that elasticities will inevitably change, which means that *in all cases*, top-down models are of limited use. (Sterman, 1991) adds that price elasticities calculated using econometrics merely show correlation, i.e., between energy prices and energy demand, rather than causality.

The above arguments are interesting for the modelling carried out for Papers II and III of this thesis, given that top-down estimates of future demand are made. In both papers, it is assumed that construction booms do not occur in the coming decades, meaning that there should be stable technological developments in the existing building stock over the same period, i.e., a modelling assumption that satisfies the criteria (Swan and Ugursal, 2009) for the use of top-down modelling. This assumption is based on the fact that major construction booms have occurred once since WWII in each European country, and that the current construction rate increases the building stock by less than 1% per year. The top-down modelling presented in Papers II and III is also based on the assumption that there are no discontinuities in price elasticities or in the rate of implementation of non-price-induced policy and technology changes. This is a classic top-down approach in which the main lever for change in energy demand is energy prices. It is used for scenarios to Year 2030 and Year 2050, respectively, and conforms to what has been described previously as a stable sector (Swan and Ugursal, 2009). Taking the aforementioned criticism of top-down modelling on board, the work in Papers II and III can be defined as 'examining different business-as-usual scenarios in the absence of any regime change that would bring about the rapid deployment of energy-efficient technologies with sensitivity analysis around energy prices'. Such top-down modelling is necessary to examine a business-as-usual scenario that incorporates both price and non-price effects. If nothing else, this can establish a baseline projection that can highlight the 'discontinuities' or 'regime changes' needed to meet energy and climate policy goals. The bottom-up modelling carried out in Paper II then complements and strengthens the results obtained. It can also be argued that because the top-down modelling in Papers II and II models physical parameters, such as unit consumption (which is an established indicator of energy efficiency), it is less susceptible to fluctuations in the economy (e.g., booms, recessions or price-hikes) than a model that simply models total energy demand. One reason for this is that (Haas and Schipper, 1998) have shown that historical improvements in energy efficiency are irreversible, i.e., impervious to downturns in the economy.

Although the mechanics of bottom-up models are usually transparent and straightforward, one criticism that has been levelled is that they impose uniform technical solutions for a modelling focus, which in reality would only occur if the consumers involved were all financial cost minimisers or members of the species humorously described as *homo-economicus* (Jaccard, 2009; Thaler and Sunstein, 2009). The point is that if a bottom-up study shows that say installing quadruple glazing windows in all dwellings in Sweden would lower energy demand substantially and save money for homeowners, this would only occur if the homeowners had the same values, priorities, and information as those promoting the study findings. (Nystrom and Wene, 1999) expanded on this type of criticism by writing that bottom-up models are prone to a reductionist fallacy because they are not anchored in the economic system in which the modelling focus exists. This entails the belief that the components in compounded energy demand will always remain the same in the future, an assumption that tacitly underlies stand-alone systems engineering models, The argument against these criticisms is that bottom-up models do not estimate the likely levels of implementation but merely show a techno-economic potential. However, it does seem that at some points in the recent past the savings estimated from bottom-up models have been over-hyped, leading to misunderstandings regarding what the outcomes from bottom-up modelling actually mean. The root of this problem may be political and media interpretations of the potential of energy efficiency to reduce energy demand, for example as estimated in the pioneering work of Amory Lovins (Lovins, 1976). The hype (real or exaggerated) surrounding the potential of energy efficiency to reduce energy demand can also be seen as the rational view of the energy efficiency industry, as represented by, for example, the mineral wool insulation sector. (Koomey, 2000) outlines a more straightforward perspective of bottom-up modelling, revealing how his team's initial efforts to model the impact of a tax subsidy for efficient HVAC equipment foundered, as it did not take account of technology learning from increased production and increased demand from the hype surrounding the subsidy. Both these latter effects are non-price effects, which Koomey writes are typically excluded from bottom-up models, thus underestimating the impact of policy measures such as subsidies. It can be argued however that Koomey merely highlights areas in which bottom-up models can be improved, rather than some of the inherent flaws of these models.

Summarising the previous arguments, the most common criticism of top-down and bottom-up models is that the one lacks the features that the other has. In other words, top-down models lack technological specificity and bottom-up models lack economic and behavioural reality. (Jaccard, 2009) writes that the problem with this is that in the pursuit of substantial technological change for environmental objectives, policymakers need to know the extent to which their policies may influence the characteristics and financial costs of future technologies, and the likely willingness of consumers and businesses to adopt these technologies. (Böhringer and Rutherford, 2008) have put it more succinctly (my comment in italics): “Endogeneity in economic responses to policy shocks (*as typically modelled in top-down models*) typically comes at the expense of specific sectorial or technological details (*as typically modelled in bottom-up models*)”. This criticism has been the motivation for the development of CIMS (Jaccard, 2009) and MCP (Böhringer and Rutherford, 2008), which are hybrid models that incorporate both top-down and bottom-up features. Paper II of this thesis responds directly to the previous criticisms (Jaccard, 2009) (Böhringer and Rutherford, 2008) by using a top-down and a bottom-up model in tandem. Thus, the work includes the technological details of a bottom-up model and the economic and behavioural *reality* of a top-down model. The modelling carried out for this thesis shows that if the EU is to achieve large cuts in energy use(as estimated using bottom-up models), additional strong policy measures must be put in place (i.e., stronger than those applied in the past, which is inherent to the outcomes of top-down modelling).

Assuming that a model is available that encompasses both technological explicitness and economic reality, such a model would struggle to address satisfactorily the general critique of Vaclav Smil (Smil, 2005). Smil describes how the biggest reduction in greenhouse gasses between 1980 and 2000 was achieved by the collapse of the Soviet Union, while the Chernobyl nuclear accident more or less ended the roll-out of nuclear power technology. According to Smil, these two events were not envisaged by modellers. He states that more sophisticated models will not fix the problems as it is simply impossible to anticipate either the kind or the intensity of unforeseen events. Reacting to these criticisms (Berndes, 2013) says that the point that Smil misses is that such scenarios are created to help decision-makers today. It is not expected that people will check scenarios in Year 2050 to see if they were correct. New scenarios are being made every year based on new information. Their main use is to help decision-making regarding investments that need to be made now. Utilities need scenarios to help them decide whether to invest or not and models are a well-established component of future planning.

(Smil, 2005) also states that modelling scenarios, rather than point forecasts, are not of much help. He states that the range of outcomes described in, for example, the four IPCC SRES scenarios (10 to 60 GTOE) is simply too wide to be of any use to policymakers. He also shows how such scenarios can be made with proverbial “back of the envelope” calculations, thereby eliminating the need for sophisticated models. In terms of the work carried out in this thesis, the scenarios used in Papers II and III differ in terms of the assumed future energy prices. The range of prices used in both papers is not greater than a no-change price scenario *versus* a 3% per annum price increase. While these scenarios clearly differ, they are not so different as to lack usefulness for policymakers, i.e., to make an efficiency policy that considers both eventualities. Nonetheless the criticisms levelled by (Smil, 2005) in terms of the range of the outcomes in the IPCC scenarios and that the scenarios could be built with very simple calculations seem to have had an impact. A response of the modelling community has been to focus on 'uncertainty' in modelling (Trutnevyte et al., 2016). In such a focus, sensitivity analysis of the main parameters used can help to evaluate the robustness of scenarios. This development is analogous to politicians wanting modellers to tell them what will happen, the modellers being reluctant to do so and instead wanting to present the answers to 'what-if?' questions, but offering a compromise to the politicians in terms of giving an uncertainty evaluation to the scenarios they present. A rudimentary sensitivity analysis of a range of energy price increases (annual increase from 0% to 5%) has been carried out in Paper II of this thesis. However, the uncertainty surrounding key modelling parameters is something that could be developed in the future. In fact, the ability to undertake a sensitivity analysis of the importance of key parameters, e.g., energy prices, insulation thicknesses or personal income, is a key benefit of both top-down and bottom-up modelling, which has perhaps been missed in the general modelling criticism outlined above (which focuses more on the energy demand estimates made from such modelling).

5. Conclusions

This thesis profiles energy demand in the EU Buildings Sector using various analytical tools. The tools include top-down econometric modelling, bottom-up building stock modelling, and index decomposition. The overarching focus of the work has been to develop tools and models that can be used as the basis for informing policymakers regarding energy use in buildings by highlighting key parameters that affect long-terms trends in energy demand. The work ranges from space heating in the Swedish residential sector to total energy demand in EU buildings. Historical data are used to establish prices, income, and other elasticities of demand, as well as to evaluate the impacts of energy efficiency policies. Projections of demand to Year 2030 and beyond are made using different price scenarios and these allow estimations of the energy efficiency gap and the implicit discount rate. The aspiration to establish important drivers of energy demand in buildings is fulfilled. Thus, the key findings for policymakers from the research are:

- In the period1990–2010, regulations were more effective than either subsidies or information campaigns at lowering energy demand for space heating in buildings in the EU-15.

- The price elasticities of energy demand calculated in Papers II, III, and IV for the period 1970/1975 to 2005/2010 are all low, varying from around -0.15 to -0.30.

- Increasing floor area per dwelling and electrical appliances per capita over the period 1990–2010 has exerted upward pressure on energy demand in the Residential Sector, while efficiency legislation and autonomous technical progress have had the opposite effect.

- Following on from the previous findings, the implementation of efficiency legislation at the historical rate is necessary to avoid runaway growth in energy demand while further reductions in demand will be more readily met with targeted measures than with price rises. This is a result of the market barriers that prevent a price signal having the desired effect and giving rise to the energy efficiency gap.

- For the case of useful energy for space and water heating in the Swedish Residential Sector, the energy efficiency gap is small at 8 TWh. Increasing energy prices in this sector has a minimal impact on reducing CO_2 emissions because the energy carrier mix used is already close to being decarbonised. For this sector, the implicit discount rate, which is an indicator of among other things, the risks and transaction costs people associate with investment decisions, e.g., efficiency measures in buildings, is 10 %.

6. Further work

The methods applied and the cases considered in the four papers of the thesis could be developed in a number of ways.

The bottom-up building stock model used in Paper I could be used to estimate the impact of EU legislation that covers buildings in relation to energy demand and CO_2 emissions. The fact that the model is set-up to cover the entire building stock of the EU makes it suitable for such an application. For example, the impact to Year 2050 of the component of the Energy Efficiency Directive that requires all new dwellings built after Year 2020 to be ‘nearly-zero’ energy buildings could be examined. Although the model does not incorporate costs, it nonetheless can give guidelines as to the effectiveness of measures such as the regulation on ‘nearly-zero’ energy houses. The model could also be used to make some preliminary assessments of the choices for the building stock in terms of accelerated retrofit vs. district heating vs. electrification.

The method used in Paper II could be applied to a different country. In doing so, it would be interesting to investigate if the energy efficiency gap calculated is of similar magnitude to that for Sweden. The data requirements would include a sufficiently detailed description of the dwelling stock and the measures that could be applied, for the bottom-up part of the modelling, while a sufficiently long time-series of energy demand, energy prices, and income per capita would be needed to establish the elasticities used in the top-down part. As an additional development, the construction of new dwellings could be introduced to the modelling.

In a development of the method applied in Paper III, the ARDL ‘bounds’ test of co-integration developed previously (Pesaran and Shin, 1999), (Pesaran et al., 2001) could be employed. Doing so would produce a more robust assessment of the level of co-integration of the dependent and explanatory variables. This is because the ARDL bounds test has several advantages over the more commonly used (Engle and Granger, 1987) tests of co-integration employed in Paper II and Paper III. First, there is no prerequisite that the variables used have to have the same order of integration. Thus, a combination of variables that are stationary I(0) and first-order non-stationary I(1) can be included. This eliminates the need for pre-testing variables to establish whether they are stationary or not. Second, the test is applicable to small sample sizes. This is advantageous given that it is well-known that the methods of co-integration (Engle and Granger, 1987), (Johansen, 1991) are not reliable for small sample sizes (Narayan, 2005). A further development of the modelling carried out in Paper III would be to introduce persons per household as an additional explanatory variable of floor area. This is because there is not a linear change in dwelling size related to the number of people living together.

The method through which policies have been quantified in Paper IV could be developed to produce a generalised method for doing so. The policy quantification carried out, which involved making a database of efficiency policies in place, could be applied to any other policy portfolio where the desire was also to carry out an empirical analysis. As described in Paper IV, policies in place are usually treated as binary variables in empirical analyses. Another promising approach could be to run a dynamic panel as opposed to a static panel. This would involve the introduction of lags of the dependent variable. This method has been pioneered by others (Filippini et al., 2014) for applications involving energy demand in the residential sector. Another refinement to the econometric model would be to use contemporary methods to examine the panel data for stationarity and co-integration.

Some of the criticism associated with using econometrically derived parameters to estimate energy demand going forward could be addressed by incorporating a computable general equilibrium model (CGE) into the work. An advantage of this approach would be to make price and income dynamics endogenous to the model. It would also allow different options for heating (accelerated retrofit vs. district heating vs. electrification) to be explored in more detail than was possible in Paper I. It would also allow rebound or fuel poverty to be incorporated. An example of such modelling is provided by (Giraudet et al., 2012) and is described in Eq. (4) for the bottom-up modelling in Section 4.

7. References

Adofo, Y.O., Evans, J., Hunt, L.C., 2013. How sensitive to time period sampling is the asymmetric price response specification in energy demand modelling? Energy Econ. 40, 90–109. doi:http://dx.doi.org/10.1016/j.eneco.2013.05.015

Alberini, A., Filippini, M., 2011. Response of residential electricity demand to price: The effect of measurement error. Energy Econ. 33, 889–895. doi:http://dx.doi.org/10.1016/j.eneco.2011.03.009

Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 32, 1131–1139. doi:http://dx.doi.org/10.1016/S0301-4215(03)00076-4

Athukorala, P.P.A.W., Wilson, C., 2010. Estimating short and long-term residential demand for electricity: New evidence from Sri Lanka. Energy Econ., Special Issue on Asian Energy in the Context of Growing Security and Environmental Concerns 32, Supplement 1, S34–S40. doi:10.1016/j.eneco.2009.08.005

Bentzen, J., Engsted, T., 2001. A revival of the autoregressive distributed lag model in estimating energy demand relationships. Energy 26, 45–55. doi:http://dx.doi.org/10.1016/S0360-5442(00)00052-9

Bentzen, J., Engsted, T., 1993. Short- and long-run elasticities in energy demand: A cointegration approach. Energy Econ. 15, 9–16. doi:http://dx.doi.org/10.1016/0140-9883(93)90037-R

Berndes, G., 2013. Personal communication with author.

Bhattacharyya, S.C., Timilsina, G.R., 2009. Energy demand models for policy formulation: a comparative study of energy demand models. World Bank Policy Res. Work. Pap. Ser. doi:http://dx.doi.org/10.1596/1813-9450-4866

Boasson, E.L., Dupont, C., 2015. Buildings: Good Intentions Unfulfilled. Decarbonization Eur. Union Intern. Policies Extern. Strateg. 137.

Böhringer, C., Rutherford, T.F., 2008. Combining bottom-up and top-down. Energy Econ. 30, 574–596. doi:http://dx.doi.org/10.1016/j.eneco.2007.03.004

Boonekamp, P.G.M., 2007. Price elasticities, policy measures and actual developments in household energy consumption – A bottom up analysis for the Netherlands. Energy Econ. 29, 133–157. doi:http://dx.doi.org/10.1016/j.eneco.2005.09.010

Boonekamp, P., Vethman, P., Gerdes, J., Sipma, J., Feenstra, Y., Pollitt, H., Summerton, P., 2011. Background study for horizontal issues concerning energy savings in the EU. Request for Services, TREN/A2/143-2007. Energy Res. Cent. Neth. Camb. Econom.

Capros, P., Mantzos, L., DeVita, N.T., A...Kouvaritakis, N., 2008. Trends to 2030-update 2007, European Commission-Directorate General for Energy in collaboration with Climate Action DG and Mobility and Transport DG, August 2010. Office for official publications of the European Communities, Luxembourg.

CEBR, 2011. British Gas Home Energy Report: an assessment of the drivers of domestic natural gas consumption. Centre for Economics and Business Research Limited.

Chateau, B., Lapillonne, B., 1978. Long-term energy demand forecasting A new approach. Energy Policy 6, 140–157. doi:10.1016/0301-4215(78)90035-6

Cowart, R., 2011. Prices and policies: carbon caps and efficiency programmes for Europe's low-carbon future. Regul. Assist. Proj. 51, 19.

Dougherty, C., 2011. Introduction to Panel Data Models, in: Introduction to Econometrics. Oxford University Press, UK.

Douthitt, R.A., 1989. An economic analysis of the demand for residential space heating fuel in Canada. Energy 14, 187–197. doi:http://dx.doi.org/10.1016/0360-5442(89)90062-5

Dulleck, U., Kaufmann, S., 2004. Do customer information programs reduce household electricity demand?—the Irish program. Energy Policy 32, 1025–1032. doi:10.1016/S0301-4215(03)00060-0

EC, 2015. Submission by Latvia and the European Commission on behalf of the European Union and its member states.

EC, 2014. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions - A policy framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final.

EC, 2012. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EC and repealing directives 2004/8/EC and 2006/32/EC. European Commission.

EC, 2011. A Roadmap for moving to a competitive low carbon economy in 2050. COM(2011)112. European Commission.

EC, 2008. Energy efficiency: delivering the 20% target. COM(2008)772. European Commission.

EC, 2006. Action plan for energy efficiency: realising the potential. COM(2006)545 545.

Ehrlich, P., Holdren, J., 1972. Review of the closing circle. Environment 14, 24–52.

Enders, W., 2003. Applied Econometric Time Series, 2 edition. ed. Wiley, Hoboken, NJ.

Enerdata, 2013. Odyssee Database [WWW Document]. URL http://www.odyssee-indicators.org

Engle, R.F., Granger, C.W.J., 1987. Co-integration and Error Correction: Representation, Estimation, and Testing. Econometrica 55, 251–76.

Enper Tebuc, 2003. Energy Performance of Buildings - Application of Energy Performance Regulations to Existing Buildings. Final report of Task B4, Enper Tebuc, SAVE II Programme 1998-2002. DG-TREN Contract 4.1031/C/00-018/2000.

Episcope, 2016. European Episcope Project [WWW Document]. URL http://episcope.eu (accessed 3.28.16).

Filippini, M., Hunt, L.C., Zorić, J., 2014. Impact of energy policy instruments on the estimated level of underlying energy efficiency in the EU residential sector. Energy Policy 69, 73–81. doi:10.1016/j.enpol.2014.01.047

Fouquet, R., 1995. The impact of VAT introduction on UK residential energy demand: An investigation using the cointegration approach. Energy Econ. 17, 237–247. doi:10.1016/0140-9883(95)00015-M

Gately, D., Huntington, H.G., 2002. The asymmetric effects of changes in price and income on energy and oil demand. Energy J. 19–55.

Giraudet, L.-G., Guivarch, C., Quirion, P., 2012. Exploring the potential for energy conservation in French households through hybrid modeling. Energy Econ. 34, 426–445. doi:10.1016/j.eneco.2011.07.010

Gujarati, D., Porter, D., 2015. Essentials of Econometrics, 5 edition. ed. Mcgraw-Hill College, Boston, Mass, USA.

Haas, R., Schipper, L., 1998. Residential energy demand in OECD-countries and the role of irreversible efficiency improvements. Energy Econ. 20, 421–442. doi:10.1016/S0140-9883(98)00003-6

Hendry, D.F., Juselius, K., 2000. Explaining cointegration analysis: Part 1. Energy J. 1–42.

IEA, 2012. IEA Energy Prices and Taxes Statistics, OECD iLibrary. doi:http://dx.doi.org/10.1787/eneprice-data-en

IEA, 2011. 25 Energy Efficiency Policy Recommendations. 2011 Update. OECD, Paris.

IEA, 2009. 2009 World Energy Outlook. OECD, Paris.

IIASA, 2010. GAINS model [WWW Document]. URL http://gains.iiasa.ac.at/models/index.html (accessed 11.4.15).

Jaccard, M., 2013. The Accidental Activist. thewalrus.ca.

Jaccard, M., 2009. Combining top down and bottom up in energy economy models, in: International Handbook on the Economics of Energy. Edward Elgar Publishing.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2004. Economics of Energy Efficiency, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Elsevier, New York, pp. 79–90.

Jaffe, A.B., Stavins, R.N., 1994. Markets for energy efficiencyThe energy-efficiency gap What does it mean? Energy Policy 22, 804–810. doi:10.1016/0301-4215(94)90138-4

Jagemar, L., 2010. Study on building regulations for space heating and their likely development in certain EU countries. CIT Energy Management, Göteborg,Sweden.

Jakob, M., 2007. Essays in Economics of Energy Efficiency in Residential Buildings: An Empirical Analysis, PhD Thesis.

Janda, K.B., 2011. Buildings don't use energy: people do. Archit. Sci. Rev. 54, 15–22. doi:10.3763/asre.2009.0050

Johansen, S., 1991. Estimation and Hypothesis Testing of Cointegration Vectors in Gaussian Vector Autoregressive Models. Econometrica 59, 1551–1580. doi:10.2307/2938278

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., Djurovic-Petrovic, M., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. Build. Environ. 45, 1683–1697. doi:10.1016/j.buildenv.2010.01.021

Koomey, J.G., 2000. Avoiding "the big mistake"in forecasting technology adoption. Presented at the Proceedings of the Energex Conference.

Kranzl, L., Toleikyte, A., Müller, A., Hummel, M., Heiskanen, E., Matschoss, K., Kockat, J., Steinbach, J., Fernández Bonata, M., Pagliano, L., Pietrobon, M., Armani, R., Burger, V., Benkmann, T., Georgiev, Z., Paunova, D., Nolte, I., Atanasiu, B., Marian, C., Lapillonne, B., Sebi, C., Zahradnik, P., Karasek, J., 2014. LAYING DOWN THE PATHWAYS TO NEARLY ZERO-ENERGY BUILDINGS A toolkit for policy makers - Main findings of ENTRANZE project (entranze.eu).

Lanza, A., Bosello, F., 2004. Modeling Energy Supply and Demand: A Comparison of Approaches, in: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Elsevier, New York, pp. 55–64.

Lovins, A.B., 1976. Energy strategy: the road not taken? Foreign Affairs.

Madlener, R., 1996. Econometric Analysis of Residential Energy Demand: A Survey. J. Energy Lit. II 3–32.

Mata, É., Kalagasidis, A.S., Johnsson, F., 2013. A modelling strategy for energy, carbon, and cost assessments of building stocks. Energy Build. 56, 100–108. doi:10.1016/j.enbuild.2012.09.037

McKinsey, 2008. Greenhouse gas abatement opportunities in Sweden. Stockholm.

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., Verbruggen, A., 2011. Annex II: methodology., in: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Edenhofer, Ottmar., 2011.

Mundaca, L., Neij, L., Worrell, E., McNeil, M., 2010. Evaluating Energy Efficiency Policies with Energy-Economy Models. Annu. Rev. Environ. Resour. 35, 305–344. doi:10.1146/annurev-environ-052810-164840

Nakata, T., Silva, D., Rodionov, M., 2011. Application of energy system models for designing a low-carbon society. Prog. Energy Combust. Sci. 37, 462–502. doi:10.1016/j.pecs.2010.08.001

Narayan, P.K., 2005. The saving and investment nexus for China: evidence from cointegration tests. Appl. Econ. 37, 1979–1990. doi:10.1080/00036840500278103

Nässén, J., Sprei, F., Holmberg, J., 2008. Stagnating energy efficiency in the Swedish building sector—Economic and organisational explanations. Energy Policy 36, 3814–3822. doi:10.1016/j.enpol.2008.07.018

Nystrom, I., Wene, C.-O., 1999. Energy-economy linking in MARKAL-MACRO: interplay of nuclear, conservation and CO2 policies in Sweden. Int. J. Environ. Pollut. 12, 323–342. doi:10.1504/IJEP.1999.002299

Ó Broin, E., 2007. Energy Demands of European Buildings: A Mapping of Available Data, Indicators and Models. Master Thesis, Chalmers University of Technology, Göteborg, Sweden.

OECD, 2008. Economic Outlook No 84: Annual and Quarterly data. OECD, Paris.

Persson, A., Göransson, A., Gudbjerg, E., 2009. Bridge over trouble water—spanning the energy-efficiency gap. Presented at the Proceedings of ECEEE, pp. 75–81.

Pesaran, M.H., Shin, Y., 1999. An autoregressive distributed lag modelling approach to cointegration analysis, in: Econometrics and Economic Theory in the Twentieth Century: The Ragnar Frisch Centennial Symposium. Cambridge University Press, 1999.

Pesaran, M.H., Shin, Y., Smith, R.J., 2001. Bounds testing approaches to the analysis of level relationships. J. Appl. Econom. 16, 289–326.

Petersdorff, C., Boermans, T., Harnisch, J., Joosen, S., Wouters, F., 2005. Cost effective climate protection in the building stock of the New EU Member States. EU Energy Perfomance Build. Dir. ECOFYS Ger.

Reiss, P.C., White, M.W., 2008. What changes energy consumption? Prices and public pressures. RAND J. Econ. 39, 636–663. doi:10.1111/j.1756-2171.2008.00032.x

Ryan, L., Moarif, S., Levina, E., Baron, R., 2011. Energy efficiency policy and carbon pricing. IEAOECD Paris.

Sanstad, A.H., Greening, L.A., 1998. Economic models for climate policy analysis: A critical discussion. Environ. Model. Assess. 3, 3–18. doi:10.1023/A:1019002620369

Schipper, L., 2010. Personal communication with author.

Silk, J.I., Joutz, F.L., 1997. Short and long-run elasticities in US residential electricity demand: a co-integration approach. Energy Econ. 19, 493–513. doi:10.1016/S0140-9883(97)01027-X

Smil, V., 2005. Energy at the Crossroads - Global Perspectives and Uncertainties, New Ed. ed. MIT Press.

Sorrell, S., O'Malley, E., Schleich, J., Scott, S., 2004. The economics of energy efficiency: barriers to cost-effective investment. Edward Elgar Publishing.

Sterman, J.D., 1991. A skeptic's guide to computer models. Manag. Nation Microcomput. Softw. Cat. 2, 209–229.

Summerfield, A.J., Lowe, R., 2012. Challenges and future directions for energy and buildings research. Build. Res. Inf. 40, 391–400. doi:10.1080/09613218.2012.693839

Swan, L.G., Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renew. Sustain. Energy Rev. 13, 1819–1835. doi:10.1016/j.rser.2008.09.033

Thaler, R.H., Sunstein, C.R., 2009. Nudge: Improving Decisions About Health, Wealth, and Happiness, Updated. ed. Penguin Books, New York.

Trutnevyte, E., Guivarch, C., Lempert, R., Strachan, N., 2016. Reinvigorating the scenario technique to expand uncertainty consideration. Clim. Change 135, 373–379. doi:10.1007/s10584-015-1585-x

Unger, T., Odenberger, M., Axelsson, E., 2011. The impact on climate of European electricity, in: European Energy Pathways: Pathways to Sustainable European Energy Systems, The Alliance for Global Sustainability. Johnsson, Filip.

Werner, S., 2006. Ecoheatcool 2005–2006, Work package 1 (The European heat market) and 4 (Possibilities with more district heating in Europe). Bruss. Belg. Euroheat Power.