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Modelling energy demand in the buildings sector within the EU

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Abstract

In the on-going effort within the EU to tackle greenhouse gas emissions and secure future energy supplies, the buildings sector is often referred to as offering a large potential for energy savings. The aim of this thesis is to produce scenarios that highlight the parameters that affect the energy demands and thus potentials for savings of the building sector.

Top-down and bottom-up approaches to modelling energy demand in EU buildings are applied in this thesis. The top-down approach uses econometrics to establish the historical contribution of various parameters to energy demands for space and water heating in the residential sectors of four EU countries. The bottom-up approach models the explicit impact of trends in energy efficiency improvement on total energy demand in the EU buildings stock. The two approaches are implemented independently, i.e., the results from the top-down studies do not feed into those from the bottom-up studies or vice versa.

The explanatory variables used in the top-down approach are: energy prices; heating degree days, as a proxy for outdoor climate; a linear time trend, as a proxy for technology development; and the lag of energy demand, as a proxy for inertia in the system. In this case, inertia refers to the time it takes to replace space and water heating systems in reaction to price changes. The analysis gives long-term price elasticities of demand as follows: for France, -0.17; for Italy, -0.35; for Sweden, -0.27; and for the UK, -0.35. These results reveal that the price elasticity of demand for space and water heating is inelastic in each of these cases. Nonetheless, scenarios created for the period up to 2050 using these elasticities and an annual price increase of 3 % show that demand can be reduced by more than 1 % per year in France and Sweden and by less than 1 % per year in Italy and the UK.

In the bottom-up modelling, varying rates for conversion efficiencies, heating standards for new buildings, end-use efficiency, and fuel mixes are applied in three scenarios. The rates for expansion of floor area and increases in living standards are the same for all the scenarios. The model outputs predict that if energy efficiency remains at the current level, then expansion of the building floor area and other increases in living standards would increase final energy demand in the EU by almost 70 % by 2050. The other two scenarios reveal the levels of improvements in efficiency that are needed to maintain energy demand at current rates or reduce it by 20 %.

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

List of publications

I. Ó Broin, E., Mata, É., Nässén, J., Johnsson, F., (2011). Quantifying the Energy Efficiency Gap for Space and Water heating in the Residential Sector in Sweden. Proceedings of ECEEE 2011 Summer Study, Belambra Presqu'île de Giens, France.

II. Ó Broin, E., Nässén, J., Johnsson, F., (2011). Modelling energy demand for space and water heating in the EU residential sector. Submitted to Energy Economics Journal, August 2011.

III. Ó Broin, E., Göransson, A., Mata, É., Johnsson, F., (2011). Modelling Energy demand to 2050 in the EU Building Stock – a bottom-up analysis. Accepted for WSED Next! Young Researchers segment of World Sustainable Energy Days in Austria in March 2012.

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

Other publications not included in this thesis:

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

Göransson, Anders; Ó Broin, Eoin; Mata, Érika (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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Introduction

The IPCC has presented scientific evidence of an increase in the global temperature over the last half century, which is unusual in the context of the climate over the previous 1,300 years, and has hypothesised that it is *very likely* that this has been caused by the excessive accumulation of anthropogenic greenhouse gases in the atmosphere (IPCC, 2007). Greenhouse gas emissions from the energy system account for 65 % of the global anthropogenic emissions total (Stern, 2006). In the EU, buildings account for 40 % of energy use and 36 % of the energy system-linked CO_2 emissions (EC, 2011). Industry, transport, agriculture, and power systems account for the remainder. These CO_2 emissions from buildings include direct emissions, which arise from the combustion of fossil fuels for heating, hot water, and cooking, and indirect emissions from the use of district heat and electricity.

The overall aim of the three papers presented in this thesis is to produce scenarios that highlight the significant parameters that affect the energy demands and climate impacts[1] of the building sector. These scenarios are in turn used to analyse various pathways to sustainability, in terms of reducing the impact on climate of the building sector. A scenario defines assumptions that are made regarding the future values of exogenous parameters, such as population, average household size, personal income, annual efficiency improvement rate, and energy prices, which will individually or in combination influence energy demand and, consequently, CO_2 emissions. Given the complexity associated with describing and quantifying the interactions between these parameters, the modelling of building energy demand is essential. 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 (World Bank, 2010).

Regarding the work described in this thesis, Paper I applies both top-down and bottom-up modelling, Paper II uses a top-down approach only, and Paper III applies bottom-up modelling. In each case, hard systems analyses are used to ascertain future demand for energy and the resultant CO_2 emissions, i.e., analyses of the energy demands of economic sectors (e.g., the residential sector, as in Papers I and II) or the energy demands of technical systems (e.g., buildings that interact with the external environment and their users, as in Paper III). In Papers II and III, soft systems analyses are also employed, which means that the interactions between system components and parameters are scrutinised to elucidate system dynamics.

A central focus of the scenarios used in the three papers is the examination of the partial influences of various technical and non-technical parameters on energy demand in buildings. Technical parameters encompass the general effects of efficiency or intensity improvements in the energy end uses of space heating, water heating, cooking, lighting and electrical

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

appliances. Their effects can be summarised and measured using *unit consumption* indicators such as; energy demand per unit of floor area, per-capita energy demand, and energy per appliance. In the residential sector, the applied non-technical parameters 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.

The division of emphasis in this work between technical and non-technical parameters reflects the dichotomous role of energy efficiency observed in recent decades. This is exemplified in Figure 1, which shows the Index Decomposition (Ang, 2004) of the change in residential sector energy demand in the EU from 1990 to 2000. As expected, increasing population (activity) and increases in dwelling size and the levels of appliance ownership (structure) exerted an upward effect on total energy demand, whereas energy efficiency (intensity) reduced energy demand. The most important outcome in Figure 1 is that the influence of non-technical parameters results in an overall increase in final energy demand, despite improvements in energy efficiency. However, the trends shown in Figure 1 are an approximation of the effects for structure and intensity. Although intensity (energy per unit floor area or appliance) is an internationally accepted indicator of progress in energy efficiency, i.e., decreases are inferred as improvements in energy efficiency, the available statistical data do not allow for distinction between the effects of improvements in energy efficiency and increases in indoor temperatures or duration of heating and duration of use of appliances. This means that it is not possible to separate completely the technical and non-technical effects observed in the historical data, and in the case of Figure 1, the effects of both structure and intensity could have been greater in terms of reflecting the changes in indoor temperatures and the levels of appliance use over the period. Paper III addresses this specific issue.

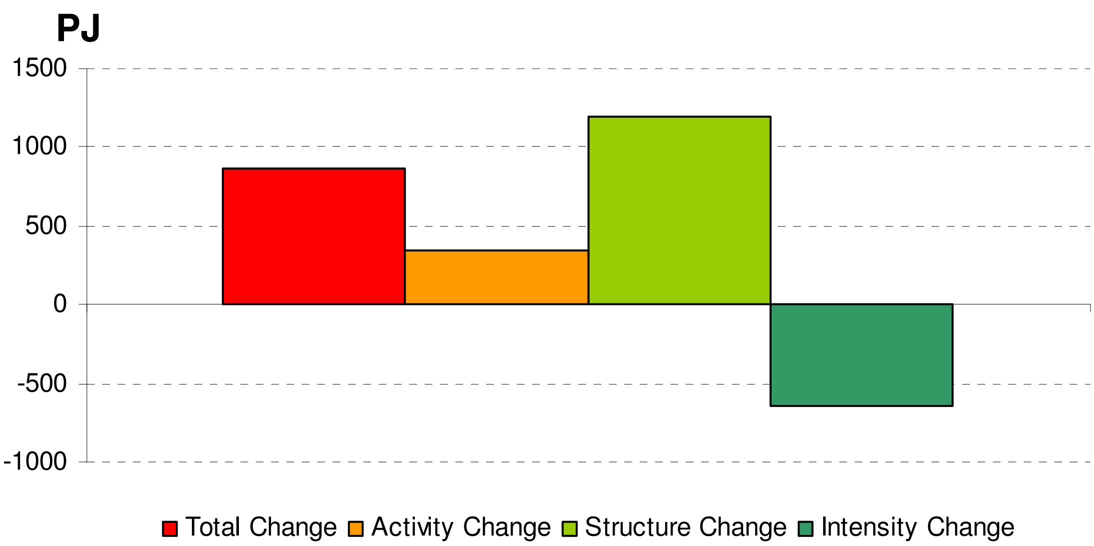

Figure 1 : Period-wise Index Decomposition of residential sector energy use in the EU-25 from 1990 to 2000. Data derived from the Odyssee Indicators Database (Odyssee Database, 2008) and using the Log Mean Divisia Index method (Ang, 2004). From Ó Broin (2007). PJ, Peta joule.

The top-down modelling (Papers I and II) uses econometrics to model the main parameters that influence energy demand for space and water heating at a national 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 are allow better estimations of the influences of price and income. A weakness of the approach is that the size of the sample used is limited to the number of annual observations available. For work that focuses on different EU countries, the best case scenario regarding data availability for energy demand and energy prices extends back to 1970, thus limiting the sample size to 35 if a typical time series from 1970 to 2005 is used. In theory, this can lead to problems with the statistical significance of the variables because econometrics would normally be carried out with far larger datasets. Nonetheless, the above-mentioned explanatory variables and time series of 35 or fewer data-points have been used successfully by others (Bentzen and Engsted, 2001; Haas and Schipper, 1998).

The bottom-up modelling (Paper III) applies assumptions related to the development of energy efficiency and standard of living increases individually to the residential and service sectors of each country examined. Thus, it explicitly separates the influences of technical and non-technical parameters. Working with, for example, the stock of existing dwellings as a single unit represents 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. Nonetheless, the model offers insights into the general role of different efficiency categories and thus can be useful for formulating policy.

Pan-European sources of data have been used for the present work, to provide data on various parameters, such as heating energy demand, building floor area, and energy prices. However, an extensive review of various pan-European data sources (Ó Broin, 2007) has revealed that 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 2005; and 2) the LBNL Buildings Database, which was put together by the late Lee Schipper and contains data from 1970 to 1995. A drawback associated with the data in the Odyssee Database is that the sources of the data are not explicitly listed. This leads to 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, the database is unique in terms of the level of end use and the time series data that it provides; the results obtained and presented in the present work (Papers I and II) are comparable to those in the literature. More recently, the GAINS Database (IIASA, 2010) has categorised energy demand in buildings according to the various end uses. This has been done for the year 2005 and for a scenario to the year 2030,based on the Primes official EU baseline (EC, 2007). Data for energy prices by energy carrier from 1978 are available from the IEA (2008), while historic data on personal income and the consumer price index are available from the OECD (2008).

Madlener (1996) has provided an overview of the top-down econometric methodologies applied in various studies that have focused on residential sector energy, while Chateau and Lapillonne (1978) have provided an example of a bottom-up approach focused on end-use. Both approaches have been employed in major studies of energy demand in buildings in the EU. In their work on buildings, the World Energy Outlook (IEA, 2009) and the Energy Technology Perspectives (IEA, 2010) used the top-down methodology (IEA, 2011). Ecofys (2004, 2005), Wuppertal and WWF (2005), UNEP (2007), Fraunhofer ISI (2009), Greenpeace International and EREC (2010), BPIE (2011), the European Climate Foundation (2011), and Ürge-Vorsatz et al (2011) have all used a bottom-up methodology. In its work on buildings, the Primes model of EU demand has used a hybrid top-down/bottom-up methodology (EC, 2007). This thesis seeks to complement these previous studies by establishing:

- the magnitude of the so-called energy efficiency gap between results from top-down and bottom-up studies (Paper I);
- up-to-date price elasticities of demand for energy for heating, and income elasticities of demand for floor space in the residential sector, which can be used in top-down scenarios (Paper II);
- a transparent bottom-up model that allows analysis of the diametric impact on energy demand of a) increasing standards of living and b) improved energy efficiency (Paper III)

The details of these topics are presented in the paper summaries below. Different levels of detail and extents of geographic coverage are adopted in each case.

Paper I: Quantifying the Energy Efficiency Gap for Space and Water heating in the Residential Sector in Sweden

Paper I describes the modelling of energy demand for space and water heating in Swedish dwellings, using top-down and bottom-up methodologies, and discusses the discrepant results obtained in the context of the so-called energy efficiency gap. The existing stock of dwellings in Sweden between 2005 and 2030 is examined in this instance. Common to the two methodologies are the energy carrier prices used, the start date for modelling, and the total energy demand for dwellings in 2005. For the top-down modelling, a standard multivariate regression equation is carried out for a data series from 1970 to 2005 of unit consumption (kWh/m^2/yr) for space and water heating on the explanatory variables of energy prices, time trend, heating degree days and the lag of energy demand,. Different scenarios of future energy prices are then used to estimate how unit consumption (and thereby, total energy demand) in existing dwellings will evolve up to 2030. For the bottom-up modelling, a physics-based building model is used to calculate the cost effectiveness of ten efficiency measures using the same prices for energy carriers as in the top-down approach. This analysis is performed for a number of archetype dwellings, which represent the building stock as a whole. Figure 2 exemplifies the results, which show an energy efficiency gap that ranges from 11 TWh for an annual energy price decrease of -2 % to 3 TWh for an annual energy price increase of 5 %. At its narrowest, the energy efficiency gap is 2 TWh (for an annual energy price increase of 4 %). The main conclusions from this analysis are that some cost-effective measures are not being realized at current (0 % price increase, i.e., 2005 prices) or even lower energy prices, and that prices obviously have a greater influence as they rise. From a policy perspective, this work empirically proves the existence of an efficiency gap for space and water heating (albeit a gap that narrows as prices rise) and suggests that a price mechanism alone will not be sufficient to achieve the full techno-economic potential of energy efficiency.

Although an annual increase of 5 % in energy prices (the maximum increase shown in Figure 2) may seem excessive, it is not without historical precedent. The average energy price increase (weighted average of residential sector energy carrier prices) for Sweden for the period 1970 to 1982 was 8.2 % per annum. This period saw energy price increases of 46 % from 1973 to 1974 and 23 % from 1979 to 1980, corresponding to the two oil crises. Prices were erratic during this period, with increases of more than 5 % in eight of the years and falls of up to 7 % in the other four years. The consumer price index in Sweden for the period 1970 to 2005 increased by an average of three points per annum, with a maximum rise of eight points for 1991 (OECD, 2008). This suggests that for this period, the price of energy increased more than the price of the average basket of goods. An annual price increase of 5 % between 2005 and 2030 (as used in Figure 2) would see prices rise from 0.07 €/kWh to 0.24 €/kWh. This represents a tripling of prices over a 25-year period. This level of increase has not occurred in the past, although a doubling of prices did occur between 1970 and 1982. Thus, while an annual price increment of 5 % continuing for 25 years appears to be a very high estimation, it has already occurred for certain 10-year periods, so it is worth exploring for academic purposes and for comparisons with smaller price increments.

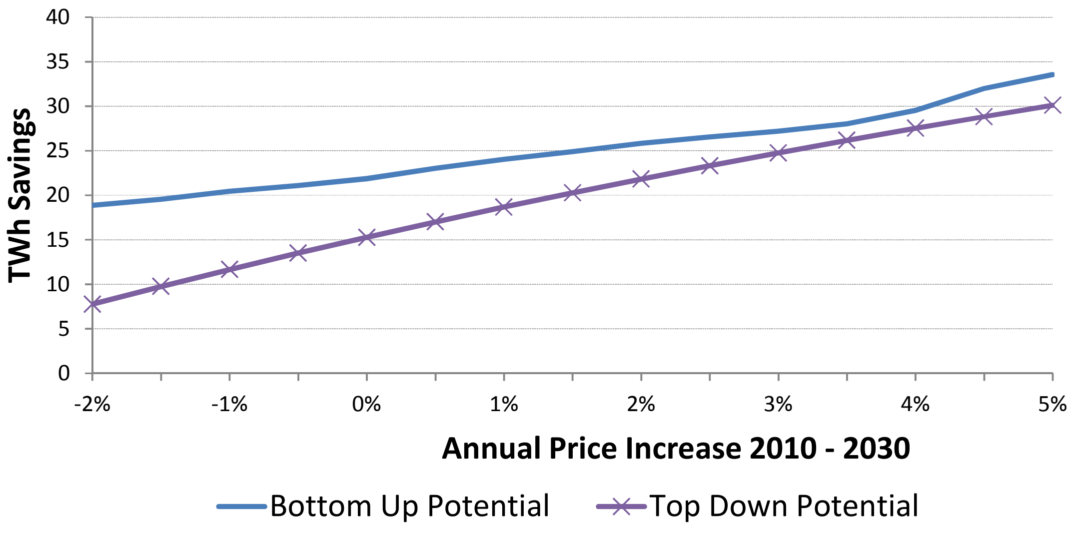

Figure 2 : Potential savings in energy demand for space and water heating in existing Swedish dwellings in 2030 derived employing the Top-Down (TD) and Bottom-Up (BU) models used in Paper I, for energy price change scenarios that range from an annual decrease of 2 % to an annual increase of 5 %. The difference between the curves at each price level represents the energy efficiency gap (Paper I, Figure 1).

Paper II: Modelling energy demand for space and water heating in the EU residential sector

Paper II models energy demand for space and water heating in dwellings using a top-down methodology similar to that used in Paper I. The total stocks of dwellings (existing and new built) between 2005 and 2050 are examined separately for France, Italy, the UK, and Sweden. These countries were chosen because of the availability of relevant data extending back to the 1970´s, their diversity in terms of climate and the extents of housing insulation, and the fact that the first three countries listed account for approximately 40 % of the total energy demand of the EU residential sector. The time series of total energy demand is decomposed (similarly to the example given in Figure 1), and each time series used is tested for stationarity. An Autoregressive Distributed Lag Model (ARDL) and an Error Correction Model (ECM) are used to model floor area per capita and unit consumption for each country. Out-of-sample testing is used to determine the model that gives the highest accuracy for the two cases. Different scenarios of future energy prices are then used to estimate how unit consumption (and consequently, total energy demand) in all dwellings will develop up to 2050, while one scenario of future income levels is used to estimate how floor area per capita will evolve up to 2050. The results for unit consumption and floor area per capita are combined with future estimations of population, collected from other sources, to calculate the total energy demand in dwellings to 2050.

Figure 3 presents the results of the modelling and compares the changes in overall energy demand for the four countries for the three price change scenarios studied. It is evident that the overall energy demand falls in all the scenarios, except in the case of the 0 % price change scenario for Italy. For France, a 3 % annual increase in price combined with the historical rate of non-price-induced technical progress results in a 1 % decrease in average annual demand. The corresponding values for Italy, Sweden, and the UK are 0.7 %, 1.3 %, and 0.6 %, respectively. Therefore, a hypothetical politically driven goal of 1 % savings per year from 2005 to 2050 would be met for France and Sweden, but not for Italy and the UK. Although such a goal does not exist, the principle is similar to that being used for the EU Energy Services Directive, wherein savings of 1 % of the Final Energy Demand are expected to be made between 2009 and 2016 (EC, 2006). The reasons for these results are multifaceted. For France, growth in floor area per capita over the scenario period is stagnant, while the efficiency of unit consumption (energy demand per unit of floor area in $kWh/m^2/yr$) improves. This offsets the impact of increased population to produce the 1 % annual decrease in total energy demand. For Italy, population growth is stagnant over the scenario period, while floor area per capita increases. The efficiency of unit consumption shows the lowest improvement of the four countries, such that overall energy demand falls but by less than 1 % per annum. For Sweden, the effects of increases in population and floor area per capita are offset by significant improvements in the efficiency of unit consumption, resulting in a decrease in overall energy demand of more than 1 % per annum. For the UK, the effects of increases in population and floor area per capita are not sufficiently offset by improvements in the efficiency of unit consumption to lead to a decrease in total energy demand of greater than 1 % per annum.

Overall, these results show that despite the counteracting influences of increasing affluence and larger floor areas, increased energy prices, regardless of whether they are procured *via* legislation, for example through tax increases, or *via* increases in the prices of crude oil, can lead to reductions in total energy demand for space and water heating in all the countries examined. These price-induced savings have the potential to make significant contributions to EU energy goals and aspirations. However, the likelihood of an annual price increase of 3 % is an issue that requires further research. In addition, given that this is top-down modelling that exploits historical relationships between energy prices and demand to generate future scenarios, it can be assumed that the effects of a direct rebound in energy demand are accounted for endogenously in the model *via* the aforementioned historical relationships. On the other hand, exploration of indirect rebound effects to other parts of the economy after energy savings derived from improvements in efficiency are beyond the scope of the present work.

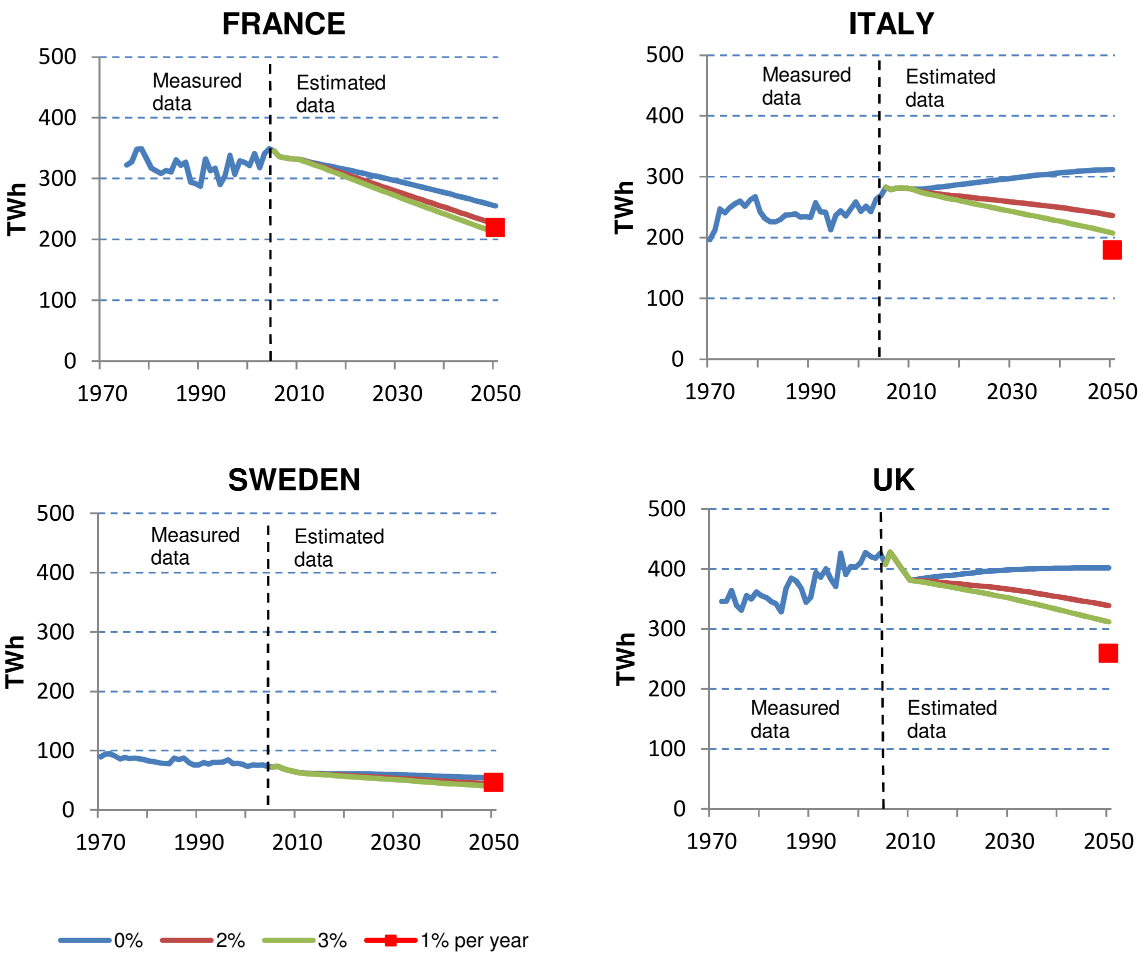

Figure 3 : Scenarios for total energy demand for space and water heating in France, Italy, Sweden, and the UK from 2006 to 2050, obtained from the modelling work carried out for Paper II. The results shown for each country are based on three annual price change scenarios (0 %, +2 %, and +3 %). The red box indicates the outcome for a hypothetical 1 % per year reduction in demand between 2006 and 2050. (Paper II, Figure 7).

Paper III: Modelling Energy demand to 2050 in the EU Building Stock

Paper III models total energy demand in buildings using a bottom-up methodology similar to that used in Paper I, although at a more aggregated level. Thus, in Paper III, the building stock is treated as a single unit and archetype buildings or individual energy saving technologies are not examined. The case is the total stock of buildings (existing and newly built) between 2005 and 2050 for the EU-27 countries. The modelling procedure distinguishes three main drivers of energy demand in the building stock: (i) growth in floor area; (ii) standard of living increase; and (iii) improvements in energy efficiency. The standard of living increase is defined as a higher demand for a service, i.e., higher room temperature or more television sets per household. Energy efficiency improvement refers, for example, to insulation that enables the achievement of a specified indoor climate with less energy or to the use of the same type of television with lower electricity consumption. This distinction is similar to the decomposition shown in Figure 1, although with an explicit separation of the effects of efficiency and increasing standard of living. This is possible because the modelling develops from a reference year and is not reliant on historical trends to determine future developments.

In Paper III, three scenarios are defined: Baseline; Policy; and Market. The Baseline scenario is a counterfactual scenario in which efficiency standards and other policies that are focused on sustainable use of energy are frozen at the 2005 levels. In the Market Scenario, the measures are supply-side-oriented and the cost to emit CO_2 is the predominant policy measure. In contrast, the Policy Scenario relies more on targeted policies that promote energy efficiency and renewable energy on the demand side (i.e., fulfilling the EU energy and climate package – the 20-20-20 targets) (Johnsson, 2011). Assumptions regarding growth of floor area and increases in standard of living are kept constant across the three scenarios, whereas for efficiency they are varied in each scenario and also divided into conversion efficiencies, heating standards for new buildings, end-use efficiencies, and fuel mixes. In the Baseline scenario, efficiency is frozen, i.e., it does not improve between 2005 and 2050. In the Market scenario, efficiency trends are set to follow those of the Primes EU baseline (EC, 2007), whereas in the Policy scenario they are set to be 20 % better than in the Market scenario, in an attempt to reflect the EU efficiency goal for 2020. It is also assumed in both the Market and Policy scenarios that electricity, district heating, and biomass will account for more than 85 % of the buildings sector fuel mix by 2050, and that the electricity and district heat supplied will for the most part be carbon-neutral.

Figure 4 shows how these three scenarios develop. Demand obviously increases in the Baseline scenario owing to the frozen efficiency improvement rates. In the Market scenario, demand falls modestly, reflecting the trends seen in recent years for efficiency improvement, while in the Policy scenario there is a 50 % fall in energy demand in 2050 compared to 2005. The corresponding CO_2 emissions for each scenario are also presented in the paper. A conclusion from the paper is that achieving larger reductions than those set out in the Market scenario will be difficult due to a plethora of obstacles, often referred to as market barriers, which prevent policy goals and aspirations being reached. These barriers include lack of knowledge and competence, transaction costs, demand for high return on investment, financing problems, and split incentives between landlords and tenants.

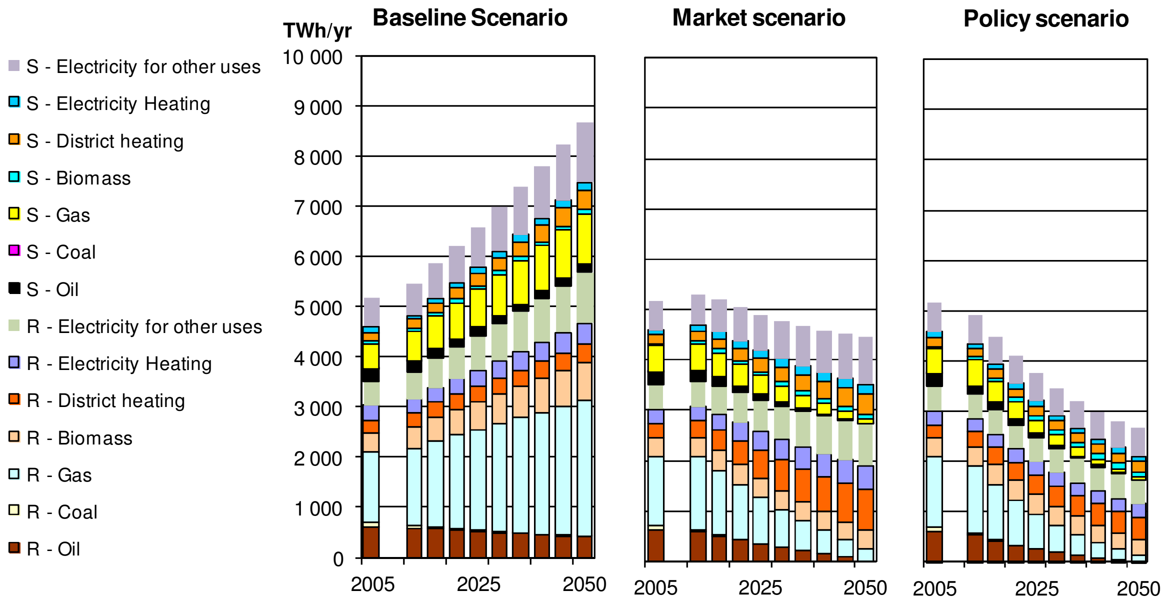

Figure 4 : Development of the energy demand of the EU-27 building stock (TWh/yr) in terms of final energy by fuels, as obtained from the modelling developed in this work. R, residential; S, service buildings; EX, existing in 2005; NEW, built in the period 20062050 (Paper III, Figure 4).

Discussion and Future Work

Most of the literature on the energy efficiency gap addresses the theoretical existence of the gap and theoretical solutions to bridging it (Jaffe et al, 2004; Sorrell et al, 2004) rather than any actual quantification of the magnitude of the gap. Paper I addresses this “gap” in the literature by using two modelling approaches (top-down and bottom-up) to quantify the energy efficiency gap. Paper I establishes the foundation for further work using the same approach for other countries of the EU, i.e., combining analyses of bottom-up techno-economic potentials with top-down economic potentials in a single study. Such studies would highlight the potential savings from the application of both fiscal and technical regulatory measures to the sector.

Paper II shows consistent results for price elasticises of demand and other relevant coefficients calculated using the two distinct methods. It highlights the impact of price- and non-price-induced technical changes on unit consumption and total demand for energy for space and water heating, and also reveals the long-term impact of income on floor area per capita. The elasticities calculated for price and other control variables provide a model of energy demand that is useful for creating scenarios of energy demand. Another approach would have been to model total demand for energy as a single dependent variable. This type of analysis was not undertaken in Paper II due to our interest in examining unit consumption and floor area dynamics separately. A control variable that represents the switch from room heating to central heating could also be included, to improve the robustness of the calculated elasticities. The following regression equation:

$$E = C * P^{\alpha} * Y^{\beta} * HDD^{\gamma} * F^{\delta} * CH^{\varepsilon} * Lag^{\zeta} * t^{\eta} \quad (1)$$

could be used for such a model, where in addition to Price (P), heating degree days (HDD), a linear trend (t), and the lag of energy demand (Lag), floor area (F), Income (Y), and the penetration of Central Heating (CH) are included. Items α to η in Equation (1) are parameter elasticities. Given the importance in fundamental economics of income, it could be treated as an instrumental variable, and introduced into Equation (1) using the two-stage least-squares methodology. A further modification of the work in Paper II would be to attempt a top-down study for all energy demands in the residential sector of the EU, as opposed to just space and water heating, which was the focus of the former paper. However, this would involve separate modelling of energy demand for heating and energy demand for electricity, mainly because the effect of weather is important for heating but not for electricity demand. This was not done in Paper II due to priority being given to the creation of a working model for one dependent variable for one country prior to attempting models for other parameters. A second possibility would be to treat the EU as one unit by combining the data from 27 countries in one panel, so as to increase the sample size to the hundreds.

Paper III describes a straightforward method for bottom-up modelling of energy demand in the EU building stock. Its value lies in it being able to examine the effects of different levels of efficiency improvement as applied to national or pan-national building stocks. Future studies might aim to develop the bases of the parameters used to measure efficiency in the thesis. This would involve further research on reasonable assumptions for future improvements in conversion efficiencies, heating standards for new buildings, end-use efficiencies, and fuel mixes.

Conclusions

The work described in the three papers of this thesis shows how top-down and bottom-up modelling approaches can be applied to the analysis of energy demand for buildings in the EU. The main parameters that have been examined in this work are the effects on energy demand of increasing energy prices and affluence and the trends in energy efficiency. The modelling results have where possible been linked to European Commission energy goals and aspirations. The modelling results also provide a framework in which fiscal and regulatory policy options can be explored and refined so as to ensure that energy demands in the EU are met in efficacious and environmentally sound manners in the future.

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