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Eoin Ó Broin, Érika Mata, Anders Göransson, Filip Johnsson

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TITLE:

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CORRESPONDING AUTHOR FAMILY NAME:

Ó Broin[a],

CORRESPONDING AUTHOR FIRST NAME:

Eoin

e-mail: eoin.obroin@chalmers.se
Phone: +46317721450
Fax: +46317723592

CO –AUTHOR 1:

Erika Mata[a]
e-mail: mata@chalmers.se

CO –AUTHOR 2:

Anders Göransson[b],
e-mail: anders.goransson@profu.se

CO-AUTHOR 3:

Filip Johnsson[a]
e-mail: filip.johnsson@chalmers.se

[a]Department of Energy and Environment,
Energy Technology,
Chalmers University of Technology,
SE-412 96 Göteborg

[b]Profu i Göteborg AB,
Götaforsliden 13, nedre,
SE-431 34 Mölndal

The effect of improved efficiency on energy savings in EU-27 buildings

ABSTRACT

Utilising energy efficiency to lower energy demand in buildings is a key policy goal of the European Commission. This paper presents the results of bottom-up modelling to elucidate the impact of energy efficiency on the EU building stock up to 2050 under three different scenarios. The modelling is performed for eight individual EU countries and a ninth hypothetical entity that represents the remaining nineteen EU countries. The scenarios highlight the roles of different levels of efficiency improvements in the context of increasing floor area and the demand for energy services. From the results it can be concluded that the EC 2020 goals for primary energy savings can be met by focusing on a combination of minimum efficiency construction standards, improved conversion efficiency standards for final energy to useful energy, and a ≥2% annual improvement in end-use efficiency applied at the useful energy level. A comparison of the results obtained in the present study for Spain with the estimates of savings documented in the Spanish Energy Efficiency Action Plan indicate that the plan could lead to the closing of the energy efficiency gap for buildings in that country by 2020.

KEYWORDS

Energy Efficiency, EU 2020 Goals, Building Energy Demand, Efficiency Scenarios, Bottom-up Modelling.

INTRODUCTION

Reducing absolute energy demand is a policy goal of the EC. This is part of the EU Climate and Energy Packet, which proposes that by 2020 there should be a 20% saving in primary energy use (relative to a projected baseline value), a 20% share for renewables in the energy supply, and a 20% reduction in greenhouse gas emissions (relative to the levels in 1990) [1]. Energy savings are to be made primarily through the deployment of efficient energy-using technologies [1]. The buildings sector in the EU is believed to be capable of delivering higher than average energy savings owing to of the number of cost-effective efficiency technologies and measures that could be deployed therein [2]. The question as to how the energy savings potential of buildings in the EU can be achieved has been explored from a number of different angles in recent years, as described below.

The work that underpins the energy savings potential of improvements in energy efficiency in buildings, as published in the first EU Energy Efficiency Action Plan [2], is the Target 2020 report [3]. The Wuppertal scenario modelling system was used to undertake a technology-oriented, sectorial, bottom-up, detailed modelling of the energy demand of the household and tertiary sectors, utilising the following scenarios: 1) business as usual; and 2) policies and measures. A heuristic (i.e., expert-based) approach was applied to formulate potentials, e.g., in the policies and measures scenario, it was assumed that for domestic electrical appliances the best available technology (BAT) in the year the report was published (2005) corresponded to the average appliance fleet value in 2020.

A more recent study that used a similar technology-oriented, sectorial, bottom-up approach to modelling is that coordinated by the Fraunhofer ISI [4], which has been used by the EC to assess the impacts of the Energy Efficiency Action Plans of individual countries. This model, which uses a simulation tool called MURE (Measures d'Utilisation Rationnelle de l'Énergie), is more detailed than that applied in the previous study [3], since it examines each country of the EU individually, uses archetype buildings, and involves more scenarios, i.e., baseline (autonomous technical development); (ii) economic potential (low policy intensity); (iii) economic potential (high policy intensity); and (iv) technical potential. The latter scenario estimates the potential savings if all end-use technologies, buildings etc. that existed in the reference year of the study (2004) are simultaneously replaced by the BAT. The other scenarios, as their names suggest, incorporate a time dimension (for example, how much could be saved by a specific year, e.g., 2030) and consider the cost effectiveness of the technologies examined.

Seminal studies in the areas of energy savings and CO_2 emission reduction potentials for buildings in the EU have been carried out by the Ecofys consultancy [5, 6]. Ecofys uses both the Built Environment Analysis Model (BEAM), which includes a simple building heat balance equation, and calculations based on the EN 832 standard, to analyse the role of thermal insulation in archetype buildings within specific climatic zones. The results of these studies have been cited extensively [e.g., 7-9].

A “building performance” approach to modeling space heating and cooling has been advocated and demonstrated [10]. In that study, they used the model to estimate final energy demand worldwide from 2005 to 2050 for: (i) a sub-optimal efficiency scenario; and (ii) a state-of-the-art efficiency scenario. The input data for their model were based on significant numbers of case studies of exemplary buildings within different regions of the world. That approach contrasts with the more common building component-based models in which the energy demand of a building is calculated (bottom-up) as the sum of the energy use for the different technologies used [3-6].

The Household Energy Demand (HED) bottom-up model [11] was used to estimate demand in the Croatian Residential Sector from 2007 to 2050. Unlike the models presented previously [3-6], that study did not examine individual energy-saving technologies but rather applied efficiency improvement rates to the end-uses of space heating and cooling, heat for water and cooking, and electricity for appliances and lighting. The energy demand of end-uses were modelled in a detailed way, e.g., the ISO 13790 standard was used to define space heating demand, and the role of floor area expansion was incorporated into the calculations.

Gouveia et al. [12] presents a bottom-up methodology to project end-use energy services demand in the residential sector in Portugal up to 2050 using the partial equilibrium TIMES model. They use 21 diverse scenarios to identify via sensitivity analysis the key parameters governing energy services demand.

Although focused on energy demand in buildings in China rather than in the EU [13] provides a detailed bottom-up model nested in a long-term, global, integrated assessment framework. The authors distinguish between rural and urban buildings and also model floor area growth. Energy demand for individual end uses such as space heating is calculated as a function of the satiated demand, personal income, and prices for energy services. The work also includes eight technology rich scenarios of demand to 2095 which differ in terms of dimensions: GDP growth, technological improvements, and the presence or absence of an idealized global carbon emissions control regime.

The World Energy Model [14], which was used to produce the IEA annual World Energy Outlook [15], involves an econometric approach for its buildings component. End-uses (in units of intensity) are regressed on explanatory variables, which represent: (i) average end-use energy prices; and (ii) a variable representing the impacts of policies and measures to reduce energy intensity and promote energy efficiency.

van Ruijven et al. [16] model and projects energy demand to 2030 in the residential sector for five World regions including Western Europe. Their approach is top-down: energy use is associated with economic activity via changes in energy intensity and efficiency and is carried out using the Timer 2.0 global energy model. The focus of the work is to analyze uncertainty in model calibration using the concept of *equifinality*, whereby there are many acceptable model calibrations that cannot easily be rejected and should be considered in assessing the uncertainty in predictions.

The reports in which the above studies are described provide valuable information regarding the possibilities to reduce energy demand and CO_2 emissions in the EU building sector. Four bottom-up models [3-6] detail energy savings potential of specific technologies, while another two bottom-up models [11,12] and a top-down model [12] detail the energy savings potentials of end-uses. The levels of cost effectiveness of the various policy or technical options have been explored [3,4] while [13] explores the trade-offs between economy-wide carbon prices and regulatory policies that would focus on building energy technology, for example through building codes and standards. In one study [10], the overall building performance is the key parameter that determines scenario outcomes. The model equations used to calculate energy savings potentials [6,10,11,13,16] present transparent reproducible approaches.

In contrast to some of the previous studies [3-6], the present work focuses on the potential for savings from energy efficiency measures applied to end-uses (e.g., heating or appliances) rather than on the energy efficiency applied to individual technologies. This analysis is performed at a national sectorial level and is less detailed than some previous studies [e.g., 3-6, 11], as archetype buildings or heat balance equations are not used and individual technologies are not examined. However, the current study allows exploration of the annual percentage improvement in efficiency that is needed to achieve savings goals, as well as the categories of efficiency that can be applied, i.e., conversion efficiency and end-use efficiency. Thus, the current approach is similar to that used in [10], as the details of the technologies used are not prescribed but rather the overall performance is examined. In addition, this study is similar to [11,12], in that end-uses rather than technologies are the focus and similar to [13, 16] in that the analysis traverses between useful, final and primary energy demand and CO_2 emissions. The aim of the present study is thus to provide a transparent description of a model that is applied for calculating energy savings potentials from efficiency in buildings on a national scale.

The rationale for focusing on efficiency in the present work is to calculate the levels of energy efficiency that are needed in existing and new buildings to meet EU energy saving goals (as described in the *EU Climate and Energy packet* [1] and the *EU Roadmap for moving to a competitive low carbon economy in 2050* [17]), in the context of increasing floor area and levels of demand for energy services. An additional reason for the focus on efficiency is that previous work by the authors [18] has revealed that increased energy prices are not sufficient to realise the range of potential cost-effective savings. The previously used version of the modeling system [19] has been improved in the present study by the discovery of a consistent way to deal with the fact that the model operates with useful and final energy at the country level, whereas EU goals are framed in terms of primary energy use.

The paper is organised as follows. In the *Methodology* section, the modelling procedure is described, as are the data sources and the scenarios used. The results are then presented, and together with the methods they are discussed both in the context of the aforementioned studies in the literature and with respect to EU goals. As a case study, the Policy Portfolio of the Spanish Energy Efficiency Action Plan [20] is discussed in the context of the scenarios described in the present work.

METHODOLOGY

The model used in this work is a hybrid that combines features of top-down and bottom-up engineering models. First, it focuses on sectorial energy end-uses and using the simulation of energy demand in buildings to determine technological choices, although it does not incorporate any economic components. Thus, this is a bottom-up model according to the previous definitions [21, 22], and it resembles the approach suggested by Chateau and Lapillonne [23]. Bottom-up models use input data from a hierarchical level lower than that of the sector as a whole, calculate the energy use levels of individual houses or groups of houses, and then extrapolate these results to represent a region or a nation [24], which is the case in the present work in that the housing stock is divided into existing (pre-2005) and new (post-2005) buildings. Second, the input data used in the model regarding future growth rates for construction, demolition, energy carrier mixes, demand for energy services, and rates of improvement of efficiency are themselves calculated from historical time series data using top-down methodologies.

The key advantages of the model used in the present work are that it:

- allows the introduction of key technical and non-technical assumptions that affect energy demand, i.e., efficiency (end-use, fuel conversion, and standards for new buildings), affluence, and demographic-related growth;
- distinguishes between useful, final, and primary energy demands; and
- estimates future energy carrier mixes and CO_2 emission levels.

The first feature listed above reflects the fact that the model separates out the three main drivers of energy demand in the building stock: (i) growth in the floor area; (ii) increase in standards of living; and (iii) energy efficiency development. The standard increase is defined as a higher demand for a service, i.e., higher room temperature or more television sets per household, while energy efficiency improvement refers to, for example, insulation that enables the maintenance of a certain indoor climate with less energy, or the same type of TV but with lower electricity consumption.

In the present work, the model is used to describe energy demand and CO_2 emissions in the building sector of the EU-27 countries, which are categorised into 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. The eight countries represent about 75% of the total final energy demand in the EU-27 [25].

Modelling Procedure

The modelling procedure begins with parameterisation of the existing building stock for a given country for a single reference year. This involves detailing the floor area and energy carriers used for heating and electricity for the two building categories of (i) Residential and (ii) Service Sector buildings[1]. Conversion efficiencies calculate useful energy demand from the final energy demand carrier mix. Useful energy demand is then subdivided into that for heating (space, water, and cooking) and that for other electrical uses (electrical appliances and lighting). This is done separately for the residential and service sectors.

Using exogenously derived assumptions (e.g., annual improvement in efficiency, annual increase in standards, targeted change in energy carrier mixes, annual construction rates), the development of useful energy demand for existing and new buildings for both sectors for the chosen scenario period is then calculated; buildings built after the reference year are treated separately from the stock that already existed in the reference year. A specific annual building renovation rate is not quantified. The percentage improvement in efficiency applied to useful energy demand rather incorporates an energy efficient renovation rate endogenously. The focus is thus on the impact of renovation on energy demand rather than on the numbers of houses renovated *per se*. The roles of behavioural changes or possible product saturation effects are not examined. Thus, the possibility of voluntary or price-induced reductions in energy demand is not taken into consideration. The scenario period can itself be divided into a number of discrete time steps. Figure 1 shows a model block diagram that shows how the model works for one discrete time period. Model inputs are shown in italics. At each discrete time period, outputs are obtained in terms of Useful energy, Final energy, Primary energy, and CO_2 emissions.

The total useful heating energy demand for the building stock (residential or service) that was in place up to the reference year is calculated as follows:

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

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 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). The same equation is used for electricity use in the pre-reference year stock. Total heating energy demand for the post-reference year building stock (residential or service) is calculated as according to:

$$NE_t = NA_t (NUC_t) (1+S_t - F1_t - F2_t - F3_t) \quad (2)$$

where NE is the total demand of energy for heating (in TWh), NA is the total floor area built since the reference year (in m^2), NUC is the Unit Consumption for heating in a new building (in $kWh/m^2/yr$), and t is a discrete time-step (in years). The same expression is used for electricity use in the post-reference year stock.

Total floor area built since the reference year (NA) is defined as:

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[1] Cooling is not specifically included in the model but is assumed to be a subset of electricity use. This is because increasing demand for cooling is more an issue that affects the electricity peak load dispatch rather than overall annual consumption [26].

$$NA_t = (A_t + NA_{t-1})(C_t) \quad (3)$$

where A is the area of the pre-reference building stock (in m^2) and C is the construction rate (in %) that captures the combined effects of more and larger buildings. A is defined as:

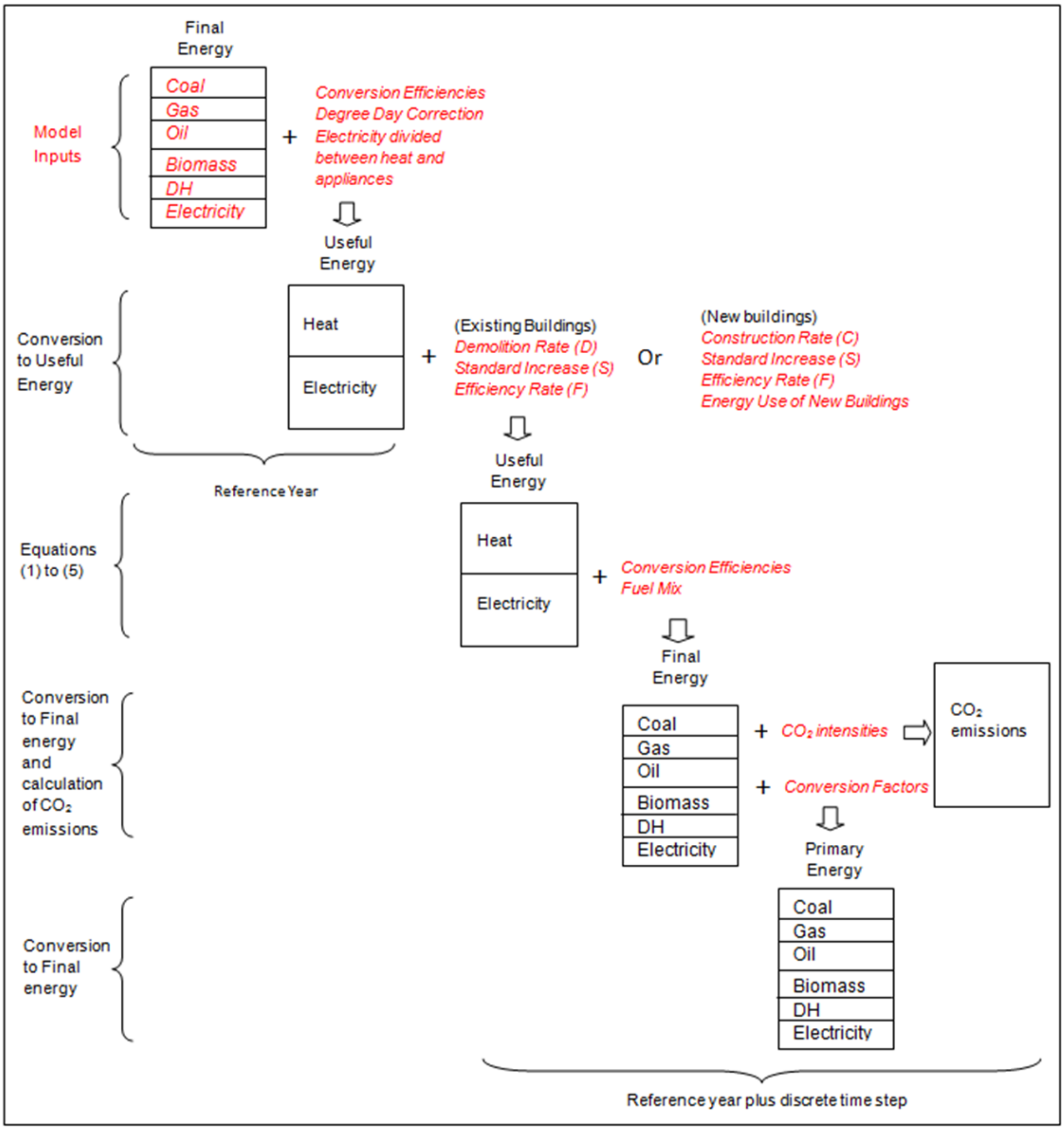

Figure 1. Block diagram illustrating how the model works for one discrete time period.

$$A_t = A_{t-1}(D_t) \quad (4)$$

Total useful energy demand (TOT) in TWh for heating (or electricity) is then defined as:

$$TOT_t = E_t + NE_t \quad (5)$$

Equations (1) to (5) are run for each discrete time-step of a scenario period. The values for D, C, S, $F1$, $F2$ and $F3$ are exogenous model inputs and as such can be kept constant for the scenario period or varied. For each discrete time-step, the total useful energy demand, TOT, for heating is converted to final energy demand using an exogenously determined energy carrier mix ratio and conversion efficiencies. Final energy demand is in turn converted into primary energy demand and the resultant CO_2 emissions, also using exogenously produced factors and intensities, which can be either kept constant for the scenario period or varied.

Note that in Eq. (1) and Eq. (2), S and F are introduced separately to allow analysis of the partial influences of standard increases and efficiency improvements. This is a key feature of the model in that it allows separate analyses of the effects of these parameters.

Scenarios used

The present work demonstrates the modelling of energy demand in the building stock of the EU, while taking into account the differences between specific countries. Three scenarios are used to model energy demand in each country for a scenario period that extends from 2005 (reference year) to 2050. 2005 is chosen as reference year based on data availability. A discrete time-step of 5 years is chosen for model iterations. Table 1 lists the model input parameters. The values listed are averages of the individual values for the nine countries examined in this work.

Table 1. Model parameter inputs for the different scenarios.

	Parameter	Baseline	Market	Policy	Source
1	**Construction rate (*C*)**	Same for all scenarios. 0.92%/yr for dwellings and 1.2%/yr for service buildings.			[27]
2	**Demolition rate (*D*)**	Same for all scenarios. 0.14%/yr all buildings.			[27]
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. Almost the same for new houses built in period 2005–2050.			[27]
4	**Standard increase: Electricity (*S*)**	Same for all scenarios. Dwellings, existing, 1.2%/yr; service buildings, existing, 1.12%/yr in existing stock. Almost the same for new houses built in period 2005–2050.			[27]
5	**Efficiency improvements: Space heating, water heating, and cooking (*F1*)**	No further efficiency measures after 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.	[27] 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.	[27] for Market Scenario.
7	**Specific space and water heating energy use in new buildings (*NUC*)**	Same as 2005. Average for EU is approximately 100 kWh/m^2/yr for space and water heating	Same as 2005. Average for EU is approximately 100 kWh/m^2/yr for space and water heating.	Approximately 40 kWh/m^2/yr in 2020. The same level is assumed after 2020.	[28]
8	**Specific electricity use in new buildings (*NUC*)**	Same as 2005.	Same as 2005.	Average of 23 kWh/m^2/yr for dwellings, and average of 64 kWh/m^2/yr for service buildings.	[27]
9	**Conversion Efficiencies (%)**	Same as 2005	Same as 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 1990 to 2005 trend	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.			[29], [30], [31].
12	**CO_2 Intensities (kg/MWH)**	Oil, 274; Coal, 342; Gas, 202.			[29]
		DH, 255; Electricity, 414; Biomass, 0.	Progressing to: DH, 2; Electricity, 10; Biomass, 0.	Progressing to: DH, 42; Electricity, 20; Biomass, 0.	[29]

In the present study, a scenario defines assumptions made regarding future levels of the exogenous parameters listed in Column 2 of Table 1. As shown in Table 1, three scenarios are applied in the present work: a Baseline Scenario, a Market Scenario, and a Policy Scenario [32]. Each scenario involves a related set of assumptions that are applied in various ways to each sector. The Baseline is a counter-factual scenario in which efficiency standards and other policies that are focused on sustainable use of energy cease to exist after 2005. This is similar in concept to the frozen technology scenario employed by [33] as their reference scenario. Therefore, the Baseline Scenario is performs worse with regard to energy efficiency than a typical business-as-usual scenario. In the Market Scenario, the measures are supply-side-oriented (e.g., RES-E (renewable electricity)), and the cost to emit CO_2 is the predominant policy measure. In contrast, the Policy Scenario relies on targeted policies that promote energy efficiency and renewable energy, which means that they are in line with the EU energy and climate package – the 20-20-20 targets of 20% saving in primary energy use (relative to a projected value), a 20% share for renewables in the energy supply, and a 20% reduction in greenhouse gas emissions (relative to the levels in 1990) by 2020 [1]. The measures in this scenario are primarily demand-side-oriented.

The same annual construction (*C*) and demolition rates (*D*) (Rows 1 and 2 in Table 1) are applied in each of the three scenarios. The same annual rates of building demolition are considered in all the scenarios, so as to isolate the effects of the other parameters modelled (i.e., parameters 5 to 9 in Table 1). In addition, despite the occurrence of construction booms in all the European Countries at one stage or another since WWII, e.g., in the 1960's in Sweden, in the 2000's in Spain and Ireland, it was decided to keep construction rates constant for each country, considering how unpredictable such booms are in reality.

The same standard increases (*S*) (Rows 3 and 4 in Table 1) are applied in each of the three scenarios. This is under the assumption that demands for energy services, and also for larger homes and commercial space, as represented by (*C*), will continue regardless of the climate and energy policy in place. It is therefore not assumed that increased regulation of energy or increased energy prices in either the Market Scenario or Policy Scenario will result in reduced demand for energy services or for smaller homes or commercial premises. Although it certainly could be argued that such effects are possible, to allow a *ceteris paribus* focus on different levels of energy efficiency, consistent assumptions with respect to standard increase are made across all three scenarios.

For the purposes of the work carried out in this paper the main difference between the three scenarios concerns the rate of improvement of the energy efficiency parameter (see rows 5 to 9 of Table 1). The motivation for the focus on efficiency has been outlined in the *Introduction*. One-off efficiency measures (*F2*) and renovation cycle efficiency measures (*F3*) are not considered in the present modelling, i.e., only continuous improvements in efficiency are applied. As shown in Table 1, efficiency is represented in three different categories: 1) efficiency improvement (Rows 5 and 6); specific energy use in new buildings (Rows 7 and 8); and conversion efficiencies (Row 9). Efficiency improvements and specific energy use in new buildings are in the case of the present work applied at the useful energy level. In the Baseline Scenario, no further efficiency improvements occur after 2005. Specific energy used in new buildings and conversion efficiencies in the Baseline Scenario are kept at 2005 levels. This obviously results in increasing demand, which in this case is driven by the growth of the building stock and the standard increase. In the Market Scenario, efficiency improvements are assumed to follow the trends observed for 2000 to 2005 in terms of autonomous technical progress and policy measures in place. Such a level of efficiency impact corresponds to that of the Baseline Scenario of the Primes model, version 2007 [34]. Efficiency improvements

(Rows 5 and 6) in the Market Scenario are assumed to also capture the effects of improvements in specific energy used in new buildings (Row 7) and conversion efficiencies (Row 8). Thus, these latter two parameters are maintained at 2005 levels in the Baseline Scenario. In the Policy Scenario, the combination of efficiency improvement, specific energy used in new buildings, and conversion efficiencies are set so that the overall EU target of savings through efficiency will be fully achieved in 2020. This EU target is comprises a target of 27% for the residential sector and a target of 30% for the services sector, measured as reductions in primary energy demand [2]. This amounts to a weighted average target of 28.1% for the two sectors combined. At the time of writing, the EC is assessing the targets from the Primes 2007 projection for 2020 [34]. Thus, for the purposes of this work, the primary energy demand in the Policy Scenario is exogenously set at 28.1% below the level of primary energy demand that transpires in 2020 in the Market Scenario, and the temporal rate of efficiency improvement needed to reach this target is assumed to continue beyond 2020.

The three scenarios also differ in terms of the energy carrier mix assumed (see Row 10 of Table 1). In the Baseline Scenario, the energy carrier mix is assumed to develop in line with the historical trends. To quantify the historic trends, each energy carrier in a national energy carrier mix has been regressed on a time trend and the coefficients obtained are used to estimate energy carrier mixes for the period 2006 to 2050. This approach is similar to that used in the IEA World Energy Model [14], albeit simpler, as the IEA uses two explanatory variables. Exceptions made to the energy carrier mix trend include the capping of oil use for heating in Ireland and Spain, despite the fact that this has been increasing in these two countries in recent years due to their housing construction booms. In the Market and Policy Scenarios, it is assumed that the direct use of fossil fuels in buildings are almost eliminated by 2050 by the force of measures carried out on both the supply and demand sides, respectively. The Market Scenario assumes a large share of district heating and electricity-powered systems (heat pumps), reflecting *greener* production of electricity, while the Policy Scenario assumes slightly fewer of these energy carriers, with the difference being made up by biomass. This is why the CO_2 intensities of the market scenario shown in row 12 of Table 1 are lower than those of the policy scenario. The difference in energy carrier mix between the Market Scenario and the EU Baseline Scenario from Primes [34] is that the Market Scenario has only half as much demand for natural gas by 2030, with the difference being divided equally between greater penetration of district heating and electricity. Whether the electricity and district heating used in the Market and Policy Scenarios are produced from renewable sources or not has been examined using other modelling tools [29] in a previous study [32].

Conversion from final energy to primary energy and CO_2 emissions (see Row 11 in Table 1) is carried out for the EU as a whole, i.e., the results for final energy demand from the individual countries are summed first. The physical energy content method for obtaining primary energy demand from final energy demand [31] is used. This method uses the physical energy content of the primary energy source as its primary energy equivalent, e.g., crude oil is allocated the same primary energy value as home heating oil. Factors for using the physical energy content method and carbon intensities for calculating CO_2 emissions from electricity and heat (see Row 12 in Table 1) have been determined by other modelling strategies [29] in a previous study [32].

Although the Baseline Scenario is counter-factual and the primary energy demands in the Market and Policy Scenarios from 2005 to 2030 are more or less known (the former is very similar to that of the Primes Scenario, while the latter aims to meet the EU 2020 savings-from-efficiency target), the use of these three scenarios is nonetheless motivated. First, the Baseline Scenario allows the overall role of efficiency to be assessed in isolation from other parameters that drive energy demand. Second, all three scenarios examine the interactions of drivers of demand at the end-use, energy carrier mix, and individual country levels. This level of detail is not available in the Primes Scenario [34].

As mentioned above, the results of the modelling for Spain are taken as a national example to examine whether the energy efficiency policy portfolio in place in that country is likely to produce the levels of savings from efficiency highlighted in this work. The choice of Spain is arbitrary and simply reflects the fact that its Energy Efficiency Action Plan has targets for savings in final energy demand for 2020.

Data Sources

Final energy demand for each energy carrier for the reference year is obtained from the GAINS database [27]. To separate electricity for appliances and lighting from electricity for other uses in the model applied in this work, a ratio calculated using data from the Odyssee database [25], which separates end-uses, is applied.

The conversion efficiency data for final to useful energy from Sweden for 2005 (the reference year) obtained from [35] are applied to all countries. This is necessitated by a lack of aggregate data for each country and reflects an assumed harmonisation of conversion efficiency standards. On the basis of a literature review that showed differences in the penetration rate of heat pumps across the EU, it was decided however to use individual estimations for each country for the conversion efficiency of electricity. Row 9 of Table 1 shows how conversion efficiencies are assumed to develop in the three scenarios to 2050. They are based on a heuristic approach, which assumes gradual improvement in the efficiency of converting household use of fossil fuels and biomass and improvements in the COP of heat pumps such that overall electricity use reaches a conversion efficiency of 2.0 by 2050.

The space heating component of useful energy demand for heating is climate-corrected. The data for degree days and degree days of reference for 2005 used to climate-correct the heating data was taken from the Odyssee Database [25]. The correction was carried out by dividing energy use for heating in 2005 by the number of degree days measured for that year, and multiplying the result by the long-run average number of degree days (degree days of reference). However, since space heating accounts for only approximately 60% of the total energy demand for heating (water and cooking account for the remainder), only 60% of the difference between the degree days measured in 2005 and the degree days of reference for the previous decades was used for climate correction.

The data regarding building construction rate (C), building demolition rate (D), efficiency improvements ($F1$), and standard increase in demand for energy services (S), which were needed for Eqs. (1) to (5) for each discrete time period from 2005 to 2030 and for floor area in 2005 (A_{2005}), were also obtained from the GAINS database [27]. However, these data categories are not available [27] in the explicit form needed for this work, which means that the data therein must be rearranged to solve for A_{2005}, C, D, $F1$, NUC_{2005}, and S. This rearrangement is described below.

All of the data in the GAINS database [27] were derived from pan-European sources [36]. The database contains data for a reference year (2005) and for a Baseline Scenario to 2030, which has been calibrated to the Primes EU baseline [34]. This means that the GAINS baseline differs from the Baseline used in this work because the GAINS baseline is a business-as-usual scenario. The main advantage of using the published data [27] rather than the data derived from Primes is that the GAINS baseline energy demand has been disaggregated to generate data at the Unit Consumption level ($kWh/m^2/year$) for different end-uses, and it also contains assumptions of future development of standard increases separated from efficiency improvements [37]. It is assumed that the values derived from the GAINS database [27] will continue to be valid for the period 2030–2050.

The floor area in GAINS database [27] was expressed in two parts: as the total floor areas of dwellings built before 2006 and of those built between 2006 and 2030. For dwellings built before 2006, a demolition rate is applied in the database to track the development of this stock to 2030. The number of dwellings built after 2006 is based on a construction rate. Both the construction and demolition rates are based on historic trends for these parameters obtained from the UNECE Housing Statistics database [36]. A floor area multiplier corresponding to the expected annual rate of growth of floor area between 2005 and 2030 [34] is applied in the database to the floor area per dwelling in 2005. The development of non-residential sector buildings is handled in a similar way. The average floor area per dwelling calculated for 2030 is combined separately with the number of existing and new dwellings in 2030, to give the total floor area for both of these categories for 2030. For the purposes of the present work, the total floor area in 2030 is compared to the total floor area in 2005, so as to obtain construction and demolition rates for the total floor area. The data on floor area in the model are thus a function of the historic rates of construction and demolition obtained from the UNECE Housing Statistics database and a floor area multiplier obtained from the Primes report [34]. The floor area for dwellings in 2005 used in this work (i.e., A_{2005} in Eq. 4) is the sum of the floor areas of apartments and houses for 2005 from the GAINS database [27], while that for commercial is taken from the database without modification.

The demolition rate, i.e., D in Eq. (1) and Eq. (4), is the compounded annual rate for 25 years obtained by dividing the pre-2006 floor area that still exists in 2030 by the floor area in 2005 and taking the 25th root. The compound annual construction rate of newly built dwellings is similarly obtained by dividing the total floor area in 2030 by the floor area that existed in 2005, as follows:

$$C_t = (A_{2030}/A_{2005}))^{(1/25)}-1) \quad (6)$$

Note that the rates differ between countries, with an average new building area rate of approximately 1% per year and an annual demolition rate of 0.14%, as shown in Table 1. In some cases, e.g., Sweden, more detailed data for floor area than those presented earlier [27] are available from national statistics, and these data have therefore been utilised.

Using the data in the GAINS database, the compound annual change in standard increase from 2005 to 2030, S, is provided by:

$$S_t = ((A_{2005}UC_{stage0}IF_{2030}/A_{2005}UC_{stage0}IF_{2005})^{(1/25)}-1) \quad (7)$$

where UC_{stage0} is the unit consumption at the least efficient of three possible efficiency levels (efficiency levels are called stages in [27]), and IF is an intensity factor that reflects increases in Unit Consumption due to standard increases. The values of A, UC_{stage0} and IF are obtained from the GAINS database. Equation (7) isolates the total change in energy demand in between

2005 and 2030 caused by standard increases. Similarly, the annual compound change in efficiency improvements, *F1,* is written as:

$$F1_t = \{[A_{2005}(\sum UC_{stagex}P_{stagex2030})/A_{2005}(\sum UC_{stagex}P_{stagex2005})]^{(1/25)} - 1\} \quad (8)$$

where P is the penetration rate of efficiency of unit consumption for each of three possible efficiency stages, and X is a number between 0 and 2. Equation (7) isolates the total change in energy demand in between 2005 and 2030 caused by efficiency improvements. The penetration rate (P) is obtained from GAINS database [27].

Equations (7) and (8) are used to calculate separately the thermal demand (space, water and cooking) and electric energy demand for both new and existing dwellings and commercial buildings. This calculation produces eight ((New or Existing) X (Electricity or Thermal) (Residential or Commercial)) separate values for standard increase (S) and efficiency improvement ($F1$) for each country. The average value obtained for the S range is 0.4% pa for heating, while that for the $F1$ values ranges from 0.6% pa to 2.7% pa for the same parameter (see Table 1).

For some of the end-uses described previously [27], energy demand was given per dwelling instead of per square metre. Equations (7) and (8) are adjusted accordingly. For newly built dwellings and newly built commercial buildings there are no data for energy demand in the year 2010 in the GAINS database [27]. Thus, the data for this parameter in 2010 are estimated by interpolation between the data for 2005 (0 TWh) and 2020. In the cases of Italy and Spain [27], different values for Unit Consumption are used for the northern and southern parts of the country. For the purposes of the calculations carried out in the present work, floor area is divided equally between the northern and southern regions when calculating Eqs. (7) and (8).

A question that arises is how the data for penetration rate (P) and intensity indicators (I) in the GAINS database [27] were calculated. This is crucial information considering that these parameters form the basis of the model inputs of the present work (see Rows 3–8 in Table 1). The penetration rates of energy-efficient technologies are estimated based on a literature review [31] and from background information supporting the Primes 2007 EU baseline [28] to which energy use is calibrated. Standard increases (called intensity indicators in [24]) are also estimated using background information from Primes 2007.

The total value for specific use of electricity in new buildings is calculated using the following component of Eq. (8):

$$NUC_t = A_{2005}\ (\sum UC_{stagex}P_{stagex2005}) \quad (9)$$

The total for specific use of new dwellings and commercial buildings for heating is obtained from an unpublished analysis of building regulations covering the eight countries [28]. Based on the previous data [28], the Unit Consumption for heating of newly built houses in the Policy Scenario decreases from approximately125 kWh/m^2/yr in 2005 to between 60 kWh/m^2/yr and 15 kWh/m^2/yr in Sweden and France, respectively, by 2030. These levels of Unit Consumption are assumed to result from the introduction of much stricter building codes following the recast of the Energy Performance of Buildings Directive (EPBD) [38].

Historic data from the Odyssee Database [25] is used to establish the estimates of long-term trends in the energy carrier mixes of buildings in the Baseline Scenario (see Row 10 in Table

1). No statistics were found regarding the historical use of district heating in Italy, France, Spain, the UK, and Ireland for the Baseline Scenario. Thus, for the entire Baseline period, the following values are applied to reflect the lack of change in the penetration of district heating: 0 TWh for Spain and Ireland; 1 TWH for the UK and Italy; and 2 TWh for France. The baseline energy carrier mix is adjusted to formulate the energy carrier mixes for the Market and Policy Scenarios, beginning with changes in the totals for district heating. The applied market share of district heating in the Market and Policy Scenarios is taken from a previous paper [39]. Thereafter, the amounts of fuels derived from oil, coal, and gas are interpolated between the reference year values and values of less than 10% in each case by 2050. At the same time, in the Market Scenario, electricity use is increased to meet 50% of the demand in 2050, with the remainder of the demand being assigned to biomass. For the Policy Scenario, electricity use is increased to 40% by 2050, with the remainder of the demand being assigned to biomass. These assumptions for the Market and Policy Scenarios for buildings are designed to designate biomass, district heating, and electricity as the main energy carriers used in buildings.

Conversion factors for final energy to primary energy (see Row 11 in Table 1) are estimated as follows using the aforementioned physical energy content method: for coal, gas, oil, and biomass, a ratio of 1:1 is used; for district heating, a loss of 10% in the conversion from primary energy to heat and a further distribution loss of 13% are assumed [30]; and for electricity, a factor of 2.3 is used for the Market and Policy Scenarios, as derived from the supply-side work of the Pathways Project [26]. The CO_2 intensities (see Row 12 in Table 1), which are also obtained from the previous report [26], are applied at the final energy demand level. The CO_2 intensities used are different in each scenario, to reflect differences in the fuel supply calculated for each scenario [26]. These differences are determined by among other things the amount of RES-E being produced. Direct CO_2 emissions from buildings refer to those produced on-site, e.g., from gas combustion for heating, while indirect CO_2 emissions refer to those produced during the production of electricity and district heating off-site.

Using the values for building construction rate (C), building demolition rate (D), efficiency improvements ($F1$), and standard increase in demand for energy services (S) derived earlier [27], the final energy demand in the Market Scenario is made to match by proxy the trajectory and amplitude of the estimate of final energy demand contained in the Primes EU Baseline Scenario [34]. However, the data in the previous publications [27, 34] relate only up to Year 2030. Nevertheless, extrapolating the Primes baseline scenario for final energy demand linearly for the period 2030–2050 produces a near-exact match of the Market Scenario for the same period.

A drawback to using the previously published data [27] for the model described in the present work is that efficiency improvements ($F1$) and the standard increase in demand for energy services (S) were applied at the final energy demand level, whereas in the model used in the present work, they are applied at the useful energy demand level. This inadvertently means that final energy demand as modelled in this work will be somewhat lower than that published previously [27], since $F1$ in [27] also incorporates efficiency improvements from conversion efficiencies and changes in the energy carrier mix. To circumvent this problem, the following strategy is taken. In modelling the Market Scenario conversion efficiencies, energy carrier mixes and standards for new buildings are locked at 2005 levels for the entire period of the scenario. Thus, although the useful energy demand modelled in the Market Scenario will be lower than in the GAINS Database, the effect of the poorer performance of conversion efficiencies, energy carrier mixes, and standards for new buildings applied will cancel out this difference in terms of final energy demand. Although not entirely accurate, this approach delivers a Market Scenario that is within 300 TWh of that of the GAINS database for 2020 and 2030.

The MURE Policy Database [20] is used to obtain the data necessary to examine the energy efficiency policies of the Spanish Energy Efficiency Action Plan.

Table 1 includes averages of the input data that were calculated for the present work. The numbers presented are averages for the EU as a whole, calculated from data used for each of the nine countries. The individual data for the nine countries (not presented) were obtained mainly through applying Eqs. (6) to (9) to the GAINS data.

The implementation of the modelling is carried out using standard spreadsheet software.

RESULTS

In this section, the results for energy demand and CO_2 emissions produced in the three scenarios are presented. The roles of the three different categories of efficiency (see Rows 5–9 in Table 1) are highlighted, and comparisons are made with the results from other similar studies.

Figure 2 gives the modelling results for final energy demand for the three scenarios examined. The data used to create Figure 2 is given in the appendix. The results shown in Figure 2 were obtained by running Eqs. (1) to (5) and subsequently applying fuel conversion efficiencies and energy carrier mix ratios for the three scenarios for each country. The Baseline Scenario (left panel in Figure 2) illustrates the development of final energy demand in response to increasing demands for floor area and energy services, i.e., all growth in demand from 2006 to 2050 in the Baseline Scenario is the result of increased floor area and increasing standards because energy efficiency improvements stop in the reference year. By 2050, the model indicates that the floor area will increase by almost 40%, whereas final energy end-demand will be almost 75% higher than it was in 2005.

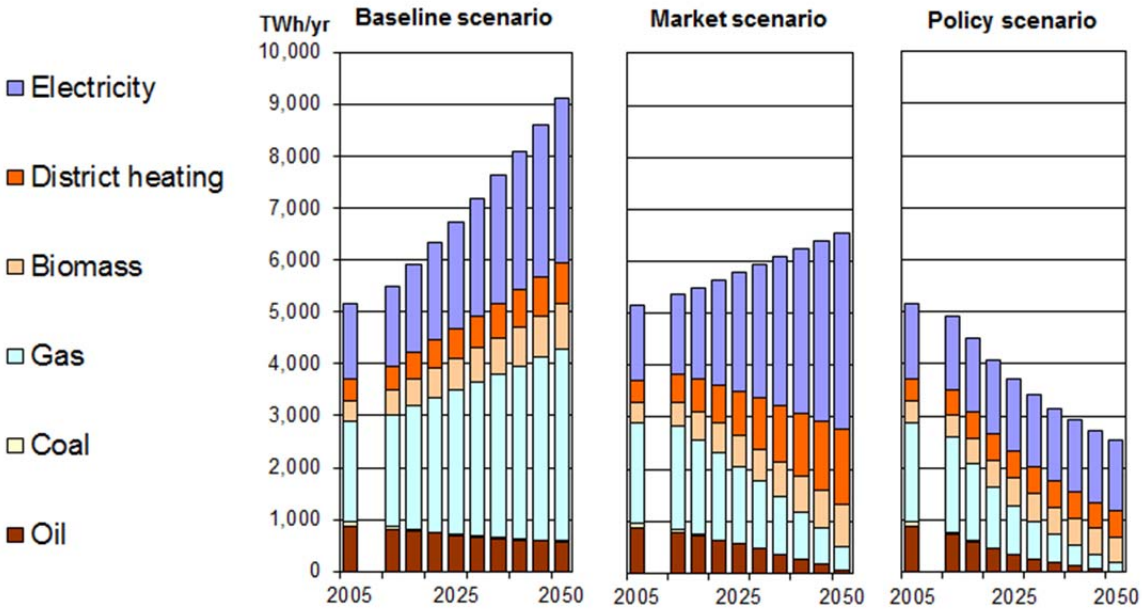

Figure 2. Development of the final energy demand of the EU-27 building stock (TWh/yr) as obtained from the modelling developed in the present work.

The Primes EU baseline, upon which the Market Scenario is indirectly calibrated, has an increase in final energy demand of 16% between 2005 and 2030, whereas the corresponding increase in final energy demand in the present study is 15%. Previous analyses [40] for Sweden suggest that the interaction between high efficiency and standard increases may result in an almost constant total final energy demand, as the higher energy performance levels of buildings, appliances, and equipment are counteracted by ever-increasing affluence. This has not proven to be the case for the EU as a whole in the Market Scenario in the present work, although the effect of modest efficiency improvements has prevented the “runaway” growth in energy demand shown in the Baseline Scenario.

The Policy Scenario (right panel in Figure 2) shows that the final energy demand is 50% lower in 2050 than in 2005. This is the result of the same large increases in floor area and standards applied in the Baseline Scenario but it is offset completely by improvements in efficiency at a rate that is set to meet the EU goal of 28% savings from efficiency in buildings by 2020. Useful energy demand in the Policy Scenario (not shown graphically) is 35% lower in 2050 that in 2005. The recently published *EU Roadmap to a Low Carbon Economy* [17] shows useful energy demands in 2050 that range from 30% higher to 20% lower than the 2005 levels for their different scenarios. The reasons given for the 20% lower scenario in the roadmap are gradual replacement of the housing stock with passive housing and a more gradual shift towards more energy-efficient and less-carbon-intensive fuels, e.g., with natural gas accounting for 30% of the energy demand by 2050. The present study shows even greater reductions in useful energy (15% greater) use due to stronger elimination of fossil fuels, e.g., with natural gas accounting for just 8% of energy demand by 2050.

Figure 3 takes the final energy demand from Figure 2 for the six largest countries of the EU (by population) to chart developments on an individual country level. Note that the data for each country in Figure 3 is not cumulative i.e. demand in Germany in 2005 was just under 1200 TWh and not 400 TWh (1200-800TWh). The national trends shown in Figure 3 are similar to those shown for the entire EU in Figure 2, although careful examination reveals that for France, Germany, and the UK there are more pronounced falls in demand in the Market and Policy Scenarios as compared with the Baseline Scenario than for the other three countries. These results are based on the assumptions made regarding the penetration of efficient technologies in each individual country. These assumptions are available elsewhere [36], and are used to determine the rates of efficiency improvements used in the present work for each country and scenario. Note that it is the averages of these assumptions for eight countries that are shown in Rows 5 and 6 in Table 1.

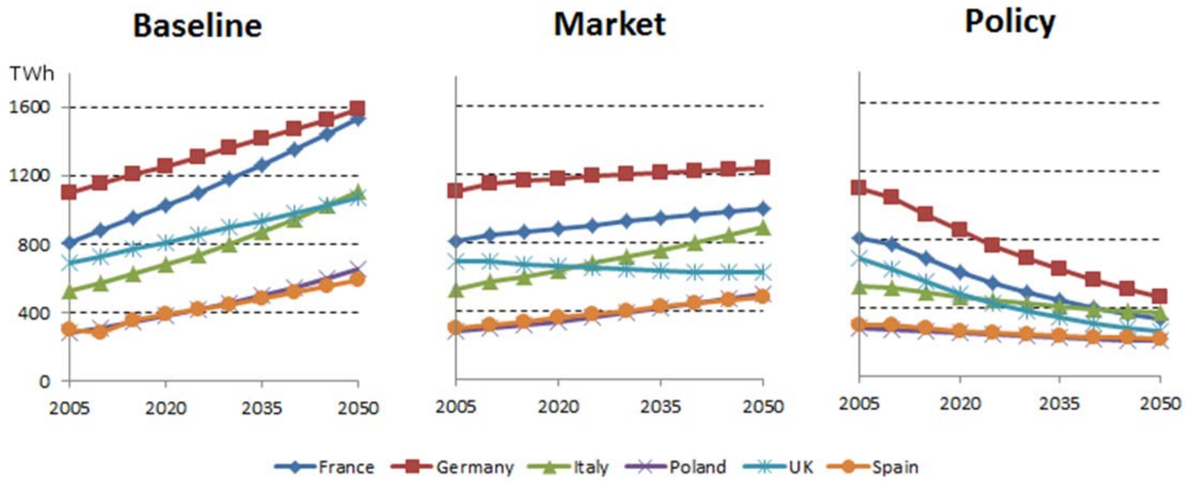

Figure 3. Development of final energy demand from 2005 to 2050 for the building stock of the six largest EU countries (by population), as obtained from the modelling developed in the present work.

Figure 2 also shows that direct use of fossil fuels in buildings is almost eliminated in both the Market and Policy Scenarios by 2050. This is the result of the model assumptions applied (see Row 10 in Table 1). Using the renewables component of Figure 2, the three scenarios can be compared with EU targets for renewables and the results of other studies. Table 2 isolates the renewables component of Figure 2 for 2020 and 2050. The proportions of the electricity and heating in Figure 2 that come from renewables were determined using another modelling strategy [29], as reported earlier [32]. The EU target of 20% renewable energy in the final energy demand by 2020 has two sub-targets that are applicable to buildings: 20 % renewable energy for heating and cooling; and 33% of electricity from renewables (Shown in parenthesis in Column 1 of Table 2). These two sub-targets are calculated for the present work as weighted averages for the EU-27 countries based on the targets for eight individual countries given in the EU legislation [41].

Table 2. Percentages of renewables in: (i) the final energy demand; (ii) energy for heating and cooling; and (iii) electricity.

% Renewables	Baseline 2005	Baseline 2020	Market 2020	Policy 2020	Baseline 2050	Market 2050	Policy 2050
Total (20%)	14	17	24	27	17	49	57
Heating and Cooling (20%)	13	16	23	26	17	52	61
Electricity (33%)	19	20	27	32	24	44	52

Comparing Columns 3 and 4 in Table 2, it is clear that in both the Market and Policy Scenarios the renewables targets for final energy demand and for heating and cooling demand for 2020 are met but that the target for electricity is not. As the electricity target is for all sectors of the economy, the result shown in Table 2 for buildings may have been offset by a greater share of electricity from renewables in other sectors. For 2050, our results show that approximately 50% of energy comes from renewables in the Market and Policy Scenarios. These are conservative estimates for the penetration of renewable, as compared to previous estimates [7, 9]. The reason that the level of penetration of renewables lies around 50% in 2050 is that although the direct use of fossil fuels in buildings has almost been eliminated by that time, all of the electricity and district heating that has replaced these fuels does not come from renewable sources. Nevertheless, if climate targets are to be fulfilled this assumes that the non-renewable proportion comes from electricity produced in plants that utilise carbon capture and storage (CCS) and from the heat generated in district heating systems [29]. The main differences in energy carrier mixes between the Market and Policy Scenarios are the lower absolute total energy demand and the greater penetration of biomass in the Policy Scenario.

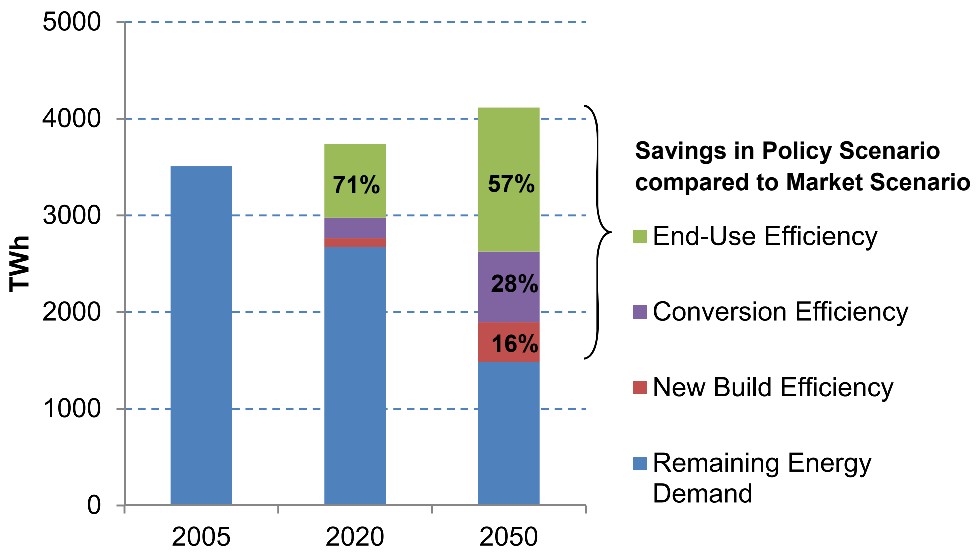

Figure 4. Savings achieved in the Policy Scenario compared with the Market Scenario in 2020 and 2050.

Figure 3 shows the differences between the Market Scenario and the Policy Scenario for the EU-27 residential sector. This is of interest because the Market Scenario corresponds to a business-as-usual scenario in terms of the rate of efficiency improvement, whereas the Policy Scenario is designed to ensure significant energy savings from improvements in efficiency. Thus, Figure 4 shows the impact that the individual contributions of the three different categories of efficiency measures applied in the present work have on final energy demand in the residential sector of the EU in the Policy Scenario. The data for Figure 4 were obtained by summing the impacts of the measures for each of the countries examined. For 2050, the three categories contribute the following proportions of total savings relative to the Market Scenario: minimum efficiency construction standards for new built dwellings, 16%; end-use efficiency applied at the useful energy level, 57%; and conversion efficiency for final energy to useful energy, 28%. The contribution of new building standards obviously will take a long time to have an impact considering the low annual construction rate. In addition the importance of measures outside of the building itself, i.e., conversion efficiency, is emphasised, as it contributes nearly 30% of the savings (not to mention the useful heat energy generated in the heat pumps, which is not represented in the graph). The results shown in Figure 3 suggest that both end-use efficiency at the useful energy level and conversion efficiency should be prioritised. Examples of end-use efficiency measures that are cost-effective for application in households in Sweden have been reported [42].

In both the Market and Policy Scenarios, the ratio of final energy demand to useful energy is incrementally decreasing, which indicates an improvement in end-use efficiency in itself. In the Policy Scenario from 2035 onwards, the amount of useful energy is actually higher than the final energy due. This is due to the improved conversion efficiencies of heat pumps assumed in the present work.

Taking the data from Figure 2 and applying final to primary energy conversion factors (see Row 11 in Table 1) produces the totals for primary energy demand for the EU-27 for each of the three scenarios produced in this work (Table 3). This is performed for the EU-27 as a whole and not on an individual country basis. In 2020, the total energy demand in the Policy Scenario is 28% lower than that in the Market Scenario as set in the model. This means however that by applying the efficiency measures at the rates listed in Table 1 and Figure 4, the EU savings through efficiency goals for 2020 (28%) can be met in the Policy Scenario.

Table 3. Primary energy demand of the EU Building Stock.

TWh/yr	2005	2020	2050
Baseline	7614	9479	14452
Market	7614	8488	12188
Policy	7614	6107	4345

Figure 5 gives the levels of direct CO_2 emissions from the building stock for the EU-27 for each of the three scenarios up to 2050. The values are for the EU-27 as a whole rather than on an individual country basis. The data for 2005, 2020, and 2050 are based on the modelling in which the fuel CO_2 intensities (from Row 12 in Table 1) were applied to the fossil fuel component in Figure 2.The data in Figure 5 for 1990 is from Primes [34] and is slightly inflated as Primes do not separate CO_2 emissions data for buildings and agriculture. . It must also be pointed out that, as explained in the *Scenarios Used* section, that the Baseline Scenario shown in Figure 5 does not correspond to a business-as-usual scenario, and thereby that emissions increase relative to the historic trend. The results for 2020 for the Market and Policy Scenarios show reductions in CO_2 emissions >10 % over the 2005 levels in both cases. This clearly meets the EU goals for that year, which correspond to a 10% reduction of the 2005 levels in the non-ETS sectors [43]. The results for 2050 shown in Figure 5 show a reduction in emissions of >90 % compared to the 1990 levels, and despite a fraction of the 1990 total being for agriculture, these results clearly meet EU aspirations for that year (-88% to 91 % for buildings by 2050 [17]). In other words, the direct emissions component of the EU CO_2 reduction goals can be met if the use of coal and oil in buildings is almost eliminated and the use of gas is 8% or lower. The contribution of energy efficiency improvements to these results is that they cause demand to be lower in the Policy Scenario than in the Market Scenario. Thus, although the CO_2 intensities of district heating and electricity are higher in the Policy Scenario than in the Market Scenario (see Row 12 in Table 1), this difference is offset by greater energy efficiency in the former scenario.

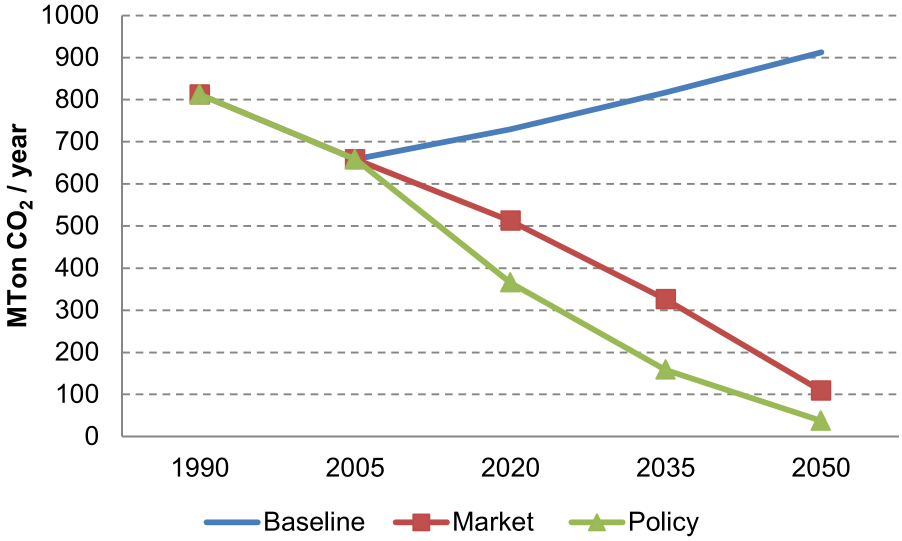

Figure 5. Development of direct CO_2 emissions from the EU-27 building stock.

Figure 6 compares the results from the current modelling (as taken from Figure 2) with those from studies of similar scope that provide results in terms of final energy demand. The data from the different reports have been harmonised for comparative purposes (as described in the Appendix). The first set of bars shows the data for 2005 (reference) for the final energy demand in buildings. The second and third sets of bars compare the results for final energy demand in the Market and Policy Scenarios of the present work with the results for 2020 from other studies.

For the year 2005 reference, all the reports are within 500 TWh of each other. MURE [4] and the WEO [13] do not provide explicit data for the EU for 2005, so the GAINS total [27] is used instead in these two cases. The GAINS baseline (business-as-usual) is itself calibrated to Primes 2007 [34], although Primes 2007 includes agriculture in its total for the services sector, thereby inflating the totals for 2005 and 2020 by approximately 350 TWh.

In the second set of bars, the results from the present work for the Market Scenario are compared with those from the Wuppertal business-as-usual scenario [3], the MURE autonomous progress scenario [4], the World Energy Outlook 450-ppm scenario [15], and the GAINS and Primes baseline scenarios.

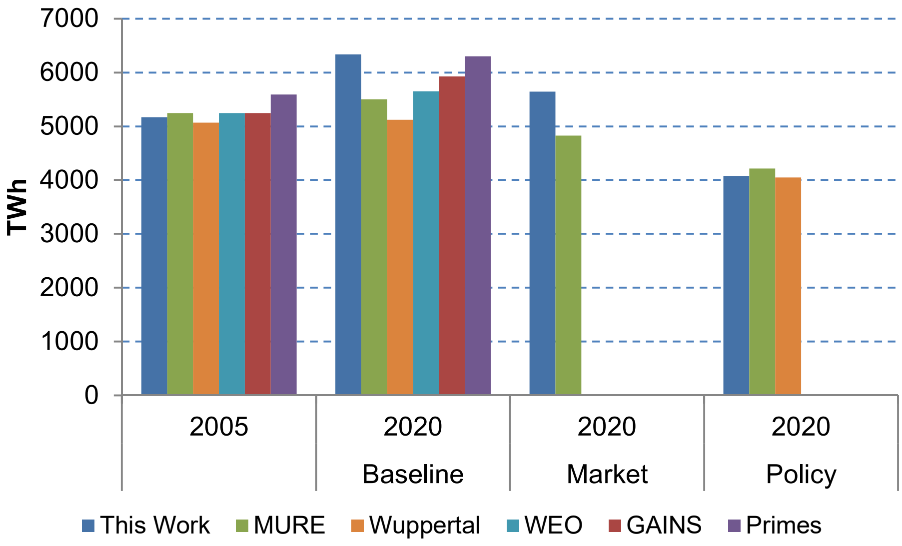

Figure 6. Comparison of the results of the present study work with corresponding studies in the literature related to future final energy demand levels in buildings in the EU-27.

The third set of bars compares the results for the Policy Scenario in the present study with those for the Wuppertal Policy and Measures scenario and the MURE technical scenario. In both cases, all the reports are again within 500 TWh of each other, with the exception of the Primes scenario in the second set of bars, although this discrepancy is attributable to its agriculture component.

The Wuppertal business-as-usual scenario is compared to the Market Scenario of the present work, as it reflects a continuation of trends in energy demand. The Wuppertal policy and measures scenario is compared with the Policy Scenario of the present work due to its assumptions related to the implementation of the EPBD [44] and its assumptions regarding best available technologies being the average for appliances and lighting by 2020. This level of ambition is similar to that needed to achieve the savings through efficiency targets of the Policy Scenario. The MURE autonomous progress scenario is compared to the Market Scenario of this work because it, like the Wuppertal business-as-usual scenario, reflects a continuation of trends in energy demand. The MURE Technical scenario envisages the removal of barriers to energy efficiency and the implementation of options that are expensive but reasonably realistic. As such, it is compared with the Policy Scenario of the present work. The WEO 450-ppm scenario is compared to the Market Scenario of this work, since although it shows an increase in demand between 2005 and 2020 it also assumes a replacement of fossil fuel use with modern biomass and other renewables over this period. The GAINS and Primes baselines for 2020 are compared with the Market Scenario of this work for the aforementioned reason that the Market Scenario has been designed to be similar to them.

The comparisons shown in Figure 6 for the Market Scenario show that the results obtained from the present work, MURE, and GAINS are similar. The reason that the Wuppertal business-as-usual scenario has a lower final energy demand in 2020 than the Market Scenario may be that it applies to the EU-25 and is based on version 2003 of Primes [45]. The comparisons show that the results from the Policy Scenario are similar to those from the Wuppertal and MURE scenarios. Given the level of detail in MURE, these results verify those obtained in the present work and support the notion [21] that simple models sometimes yield results that are as accurate as those supplied by more complicated models. Comparisons with

ETP [46] are not presented in Figure 6 as they are for 2050, and comparisons with Ecofys [5,6] are not included in Figure 5 since they do not provide results in terms of final energy demand.

Figure 7 compares the CO_2 emissions (direct plus indirect) from the building stock, as obtained from the present modelling, with those from two similar studies that provide results for CO_2 emissions. Note that the ETP [46] has 2010 as its reference year and covers OECD Europe. The Baseline for the present work assumes no improvement in efficiency over the scenario period, whereas the baseline for the ETP has no new energy and climate policy introduced during the scenario period [46]. The ETP Blue Map scenario [46], the Wuppertal Policy and Measures scenario [3], and the Policy Scenario of this work are compared in the fourth set of bars. Both the ETP Blue Map and the Wuppertal Policy and Measures scenario have greater CO_2 mission reductions in 2020 than the Policy Scenario of the present work, although all the scenarios yield values within 150 MTonnes of each other. The ETP Blue Map has a greater focus on technology and covers a greater geographical area than the Policy Scenario, with the former parameter leading to its lower CO_2 emission levels. While the Wuppertal Policy and Measures scenario has a technological focus similar to that of the present work, its lower baseline level and slightly smaller geographical area produce the lower CO_2 emission levels. The comparisons shown in Figure 6 for all three scenarios show that the results from the present work, ETP, and Wuppertal are similar, thereby providing verification of the work presented in this paper. The results from Ecofys [5, 6] or Primes [34] are not included as they only contain direct emissions. Figure 7 contains a black line, which represents the EU CO_2 emissions target for 2020, i.e., a 10% reduction in the 2005 levels in the non-ETS sectors [43]. Figure 7 shows that both the Market Scenario and Policy Scenario are adequate pathways to EU CO_2 reduction goals, although they are heavily dependent upon complementary action on the supply side. Put another way, the EU CO_2 reduction goals can be met with a combination of the efficiency measures that lead to the levels of final energy demand shown in the Market and Policy Scenarios in Figure 2 if and only if the energy carrier mix and CO_2 intensities described in Table 1 are implemented.

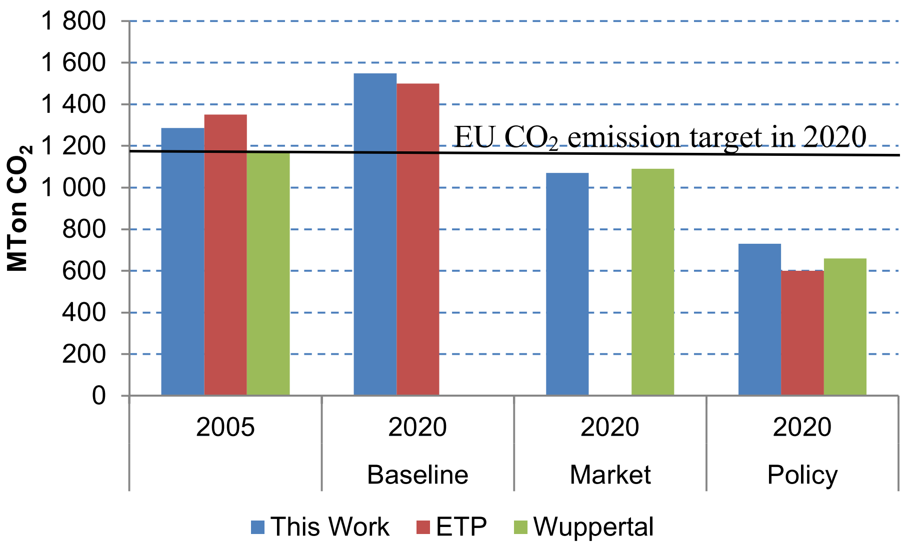

Figure 7. Comparison of the results from the present work with those from corresponding studies in the literature with regard to CO_2 emissions (Mt/yr) and CO_2 goals for buildings (direct plus indirect emissions) in the EU-27.

In summary, the EU goals with respect to primary energy savings can be met in the Policy Scenario by focusing on a combination of minimum efficiency construction standards for newly built dwellings, end-use efficiency applied at the useful energy level, and conversion efficiency standards for final energy to useful energy. If combined with efforts on the supply side, these measures could also contribute to meeting EU goals for CO_2 emissions. Comparisons with other studies, which are generally more detailed, validate the approach used in the present work.

DISCUSSION

Although the present work reveals the rates of improvement in energy efficiency that are needed to achieve the EU savings from efficiency goals for 2020, the implementation of these rates is in no way guaranteed. [47] for example describe how the implementation of energy regulations for new buildings constructed in the UK between 2006 and 2009 was only found to have been carried out to specification in a third of the 404 cases they studied. The historical trend in improvement of efficiency is represented by the Market Scenario, while the Policy Scenario, with its imposed 28% primary energy reduction, generally involves more ambitious rates than those seen to date and would undoubtedly require a massive demand-side effort. The revelation at the time of writing (July, 2012) that the EC has *de facto* reduced its overall primary energy savings goal from 20% to 17% during negotiations surrounding the forthcoming Energy Efficiency Directive indicates the practical difficulties associated with savings implementation [48]. In Denmark, which has been held up as an example for other EU countries of how efficiency policies should be implemented, the primary energy supply for heating has been reduced to two-thirds of that prior to 1973, even though the heated space area has increased by more than 50% over the same period [49]. This level of effort is in line with what is needed to implement the Policy Scenario. Specifically, the Policy Scenario would involve an annual improvement in end-use efficiency of >2% per annum (see Rows 5 and 6 in Table 1). It has been suggested that improvement in efficiency of 5% per annum (7% for new buildings) is possible [50]. The work conducted by Blok [50] includes the effects of conversion efficiencies and fuel switching, which makes a 2% improvement in end-use efficiency per annum seem plausible. However, such a level of efficiency improvement would require a demand-side effort of the scale described in Golubchikov's "5 In" analytical scheme [51], whereby a combination of investment, information, innovation, incentive, and initiative is required to bring about significant levels of building renovation, or that described in the IEA Task 37 handbook "From demonstration projects to volume market" [52] or indeed the Danish space heating case [49].

Table 4 shows that the differences in final energy demand between the Market and Policy Scenarios are 1200 TWh in 2020 and 3300 TWh in 2050. The difference between the Market Scenario and Policy Scenario calculations (Figure 2) could be interpreted as illustrative of the so-called 'energy efficiency gap'. The orthodox economic theory behind the existence of the energy efficiency gap [53] and an alternative view that focuses on the role of transaction costs and 'bounded rationality' [22] are presented elsewhere. Another paper [54] describes (using the example of Sweden) the historical obstacles to accomplishing energy efficiency measures on the demand side at the rate specified by the Policy Scenario, as these measures involve millions of decision makers, often non-professionals, and many difficult decisions. There are many uncertainties and options, which are difficult to evaluate for those who seldom work with energy efficiency issues. This contrasts with the carrying out of activities in the energy supply sector, in which the projects are generally much larger and require a limited number of decisions and these decisions are often made by professionals. A quantitative calculation has been made [18] of the gap size for *space and water heating in the Swedish residential sector*[2], understood as the gap between the savings in energy that could accrue from the implementation of all cost-effective energy efficiency measures known to exist (i.e., considering only direct costs from a consumer perspective) and the savings that accrue from the energy efficiency measures that are on average actually implemented in the long run. As the Market Scenario represents a continuation of historical trends (in terms of energy efficiency improvement) the difference shown in the fourth row of Table 4 is an approximation of the gap following the definition given in [18].

Table 4. Total Useful Energy of the EU Building Stock.

Total Useful Energy (TWh)	2005	2020	2050
Market Scenario	4220	4800	6000
Policy Scenario	4220	3600	2700
Difference (Gap)		1200 (25%)	3300 (55%)

The case of Spain is examined to assess the efforts being made in a sample country to achieve savings of the magnitudes outlined in the Policy Scenario, and thereby close the energy efficiency gap. Specifically, the quantitative assessments of energy savings in 2020 from on-going relevant policies of the Spanish Energy Efficiency Action Plan (as taken from the MURE database [20]) are compared to the savings through efficiency estimated in the Policy Scenario of the present work. The Spanish Efficiency Action Plan for 2011–2020 was created pursuant to the EU Energy Services Directive [55]. The plan envisages savings in the final energy demand of buildings through efficiency amounting to 33 TWh for Year 2020, as compared with the final energy demand in 2007 [20].This is similar to the results obtained in the present study for Spain whereby the final energy demand in the Policy Scenario is 35 TWh lower in 2020 than in the reference year of 2005. This suggests that the overall ambition of the Policy Scenario in the present work is in accordance with a practical implementation plan in at least one country of the EU.

The individual policy measures of the Spanish Energy Efficiency Action Plan are listed below, and they are classified here into the same three categories of efficiency examined in the present work. The estimated savings from each measure (as obtained from the MURE database [20]) and the database policy reference numbers are shown in parentheses.

- Saving from applying minimum efficiency construction standards for newly built buildings
    - Construction or rehabilitation of near-zero-energy buildings (9 GWh) (SPA39, SPA49)
    - Construction of new buildings and rehabilitation of the existing ones with high-energy qualification (3 TWh) (SPA33, SPA36)
- achieved through increased Conversion Efficiency

[2] The energy efficiency gap was calculated *by comparing the energy use in 2030 for space and water heating in existing Swedish residential buildings*, as calculated with a bottom-up component-based model, to that obtained using a top-down regression-based model. Note that this is different from the work in the current paper in three aspects: a) time frame, i.e., the present work is up to 2050; b) end-uses assessed, i.e., the present work also includes electricity; and c) the number of buildings/subsectors assessed, i.e., the present work also includes new buildings.

    - Improvement of the energy efficiency of the thermal installations in existing buildings (11 TWh) (SPA31. SPA35)
- achieved through increased End-Use Efficiency
    - Renewal of the thermal casing in existing buildings (9 TWh) (SPA30, SPA34)
    - Improvement of the energy efficiency of the indoor lighting installations in existing buildings (10 TWh) (SPA32, SPA37)
    - Improvement of the energy efficiency of the electric appliances stock (1 TWh) (SPA22)
    - Improvement of the energy efficiency of commercial refrigeration installations (19 GWh) (SPA48)

For the measures listed above, the percentages of contribution of the three categories of measures are 9%, 32%, and 59%, respectively. In the Policy Scenario of the present work, the percentages of contribution of the same categories of measures towards energy savings in Spain in 2020 are 12%, 21%, and 67%, respectively. The percentages of contribution of measures are compared because the savings listed in the Spanish Energy Efficiency Action Plan are with respect to 2007 and the savings for Spain given in the present work are the differences between the results in 2020 from the Market and Policy Scenarios. This comparison suggests that the relative importance placed on the different categories of energy efficiency outlined in the Policy Scenario of the present work (see Table 1) is similar to that given in the Energy Efficiency Action Plan of at least one EU country. In general, the above comparisons indicate that from a technical point of view the Spanish Energy Efficiency Action Plan can close the energy efficiency gap for buildings in that country. Such comparisons could be extended to other EU countries to develop further this analysis.

The significance of increasing floor area and demand for energy services has not been explored in detail in this work. That is to say that only one scenario each for these two parameters has been used in the present work, and the data for these scenarios have been taken from an exogenous source, the GAINS database [27]. Further work could involve a sensitivity analysis of the roles of the estimates for future growth in floor area and demand for energy services, as represented by the construction rate and standard increase used in this work. Furthermore, the estimates made in this work for floor area and demand for energy services to 2050 have not been compared to those from other sources, which is a topic that warrants further study. In addition, explicit modelling of floor area that takes into account parameters such as standard of living could also be performed using econometrics, as described previously [56]. While the contributions of increasing floor area and demand for energy services to increasing energy demand cannot be ignored, the magnitudes of these contributions could be explored further.

CONCLUSIONS

A bottom-up model that employs three diverse scenarios has been used to estimate energy demand and CO_2 emissions from buildings for the EU-27 to 2050 under three different scenarios. The results show that final energy demand increases significantly in a scenario in which improvements in efficiency cease after 2005, due to continuous increases in building floor area and demand for energy services. The results also show that the final energy demand can be reduced by 50% compared to 2005 levels if efficiency improves at over 2% per annum, and that the EU CO_2 reduction goals can be met if and only if the remaining energy carrier mix evolves to consist mainly of electricity and district heating produced from carbon-neutral sources and biomass. The actualisation of this scenario nonetheless imposes a tremendous challenge on the success of targeted policies. The combined importance of continued implementation of policies that focus on three different categories of efficiency, end-use, conversion, and new buildings, is also shown in the present study. A comparison of the results from the Policy Scenario from the present work with estimates of savings from the Spanish Energy Efficiency Action Plan demonstrate that the plan could lead to the closing of the energy efficiency gap for buildings in that country by 2020.

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APPENDIX

1. Assumptions

This section describes how the data from different studies are harmonised so as to facilitate the comparisons shown in Figure 6.

MURE [4] gives percentage savings of 7.2%, 18.6%, and 28.9% in 2020 for their low policy intensity, high policy intensity, and technical potential scenarios, respectively. These percentages are applied to the GAINS [27] baseline total for the EU-27 for 2020, which is 5926 TWh.

The WEO [15] gives 0.5% as the increase in energy demand between 2007 and 2020 in its 450 scenario for OECD+ countries (i.e., the OECD countries plus those EU countries that are not members of the OECD). This percentage is applied to the GAINS total for 2005, which is 5243 TWh.

Wuppertal and WWF [3] give potential annual savings of 1.4% and 3.5% for their Baseline and Policy and Measures scenarios, respectively, for the Tertiary sector. These percentages are applied to the GAINS total for 2005 for the Tertiary Sector (1676 TWh) for each subsequent year up to 2020. The totals obtained are then added to the Baseline and Policy and Measures scenario totals for 2020 for the residential sectors, as reported by Wuppertal and WWF.

2. Tables of Final Energy Demand Fuel Mixes listed in Figure 2.

Table A1: Data for the Baseline Scenario in Figure 2.

Baseline (TWh)	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
RESIDENTIAL										
Oil	613	584	573	553	524	496	472	447	423	412
Coal	95	49	29	13	14	14	14	14	14	14
Gas	1,401	1,542	1,717	1,866	2,012	2,159	2,302	2,441	2,581	2,716
Biomass	362	413	465	511	547	582	617	665	712	758
District heating	265	295	303	308	318	329	339	350	360	369
Electricity Heating	291	267	290	306	323	340	359	376	394	410
Electricity other	485	538	596	659	726	799	877	962	1,053	1,152
SERVICES										
Oil	254	225	194	180	171	161	151	155	158	162
Coal	6	5	5	5	5	5	5	5	5	5
Gas	511	607	670	720	766	813	862	903	945	989
Biomass	46	61	66	70	75	79	84	88	92	96
District heating	167	182	209	236	263	291	321	353	385	420
Electricity Heating	108	86	96	107	118	130	142	153	163	174
Electricity other	568	638	716	799	889	985	1,089	1,201	1,322	1,452

Table A2: Data for the Market Scenario in Figure 2.

Market (TWh)	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
RESIDENTIAL										
Oil	616	591	535	475	411	343	272	197	118	36
Coal	96	33	18	0	0	0	0	0	0	0
Gas	1,390	1,464	1,327	1,204	1,075	940	798	651	497	337
Biomass	362	386	450	482	489	504	533	561	593	635
District heating	261	350	407	487	572	653	729	808	886	961
Electricity Heating	297	270	370	473	581	692	808	928	1,052	1,179
Electricity other	485	527	572	619	669	722	779	838	901	968
SERVICES										
Oil	255	202	185	165	144	121	97	71	43	13
Coal	6	0	0	0	0	0	0	0	0	0
Gas	517	546	506	463	417	367	314	258	199	136
Biomass	46	68	87	88	101	112	127	143	159	179
District heating	167	182	208	249	282	320	356	394	433	472
Electricity Heating	102	122	153	190	229	269	312	358	405	455
Electricity other	568	624	684	747	812	881	952	1,027	1,106	1,188

Table A3: Data for the Policy Scenario in Figure 2.

Policy (TWh)	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
RESIDENTIAL										
Oil	616	540	433	336	255	187	131	84	45	12
Coal	96	31	16	0	0	0	0	0	0	0
Gas	1,390	1,340	1,081	854	664	507	378	272	183	111
Biomass	362	357	401	415	413	408	400	390	381	371
District heating	261	319	326	339	341	340	338	334	328	321
Electricity Heating	297	246	254	252	245	236	226	215	204	194
Electricity other	485	481	478	476	475	474	473	473	474	475
SERVICES										
Oil	255	185	151	120	93	70	50	33	18	5
Coal	6	0	0	0	0	0	0	0	0	0
Gas	517	501	413	335	267	209	160	118	82	51
Biomass	46	62	79	97	108	117	123	127	131	134
District heating	167	164	172	173	174	174	175	175	175	174
Electricity Heating	102	112	112	110	106	102	98	95	91	88
Electricity other	568	566	569	572	577	583	589	597	606	615