Energy usage and technical potential for energy saving measures in the Swedish residential building stock

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Abstract

This paper provides an analysis of the current energy usage (net energy and final energy by fuels) and associated carbon dioxide (CO_2) emissions of the Swedish residential building stock, which includes single-family dwellings and multi-family dwellings. Twelve energy saving measures (ESMs) are assessed using a bottom-up modeling methodology, in which the Swedish residential stock is represented by a sample of 1,400 buildings (based on data from Year 2005). Application of the ESMs studied gives a maximum technical reduction potential in energy demand of 53%, corresponding to a 63% reduction in CO_2 emissions. Although application of the investigated ESMs would reduce CO_2 emissions, the measures that reduce electricity consumption for lighting and appliances (LA) will increase CO_2 emissions, since the saved electricity production is less CO_2-intensive than the fuel mix used for the increased space heating required to make up for the loss in indirect heating obtained from LA.

Definitions and nomenclature

End-use	*End-use* is the ultimate specific use for the energy. In the building sector, the end-use categories are: space heating; hot water; and electricity (for lighting, appliances, and cooking).
E_{net}	*Net energy* is the energy required to satisfy the specific energy end-use in a building, excluding conversion losses in the technical systems of the building. It is also commonly referred to as '*useful energy*'.
E_{final}	*Final energy* is the energy supplied to the building, including conversion losses in the technical systems within the building. It is also commonly referred to as *'delivered energy'* or *'end energy use'*.
A_{temp}	*Heated floor area* is the floor area to be heated to a temperature above 10ºC; it is limited by the inner side or the envelope.
BOA	*Residential floor area* is the total area of the dwellings, excluding common areas (e.g., staircases) and the area occupied by walls.

Acronyms

ESM	Energy saving measure
GHG	Greenhouse gas
HW	Hot water
LA	Lighting and appliances
MFD	Multi-family dwelling
SFD	Single-family dwelling
SH	Space heating

1. INTRODUCTION

In addition to its obligations under the Kyoto Protocol agreement[1], the European Union (EU) is committed to reducing its overall greenhouse gas (GHG) emissions by at least 20% by 2020, as compared with the levels in 1990 (EC, 2008). Based on bottom–up studies, the IPCC (2007) has calculated and shown that the building sector, among all the sectors examined, currently has the greatest potential for low-cost carbon dioxide (CO_2)[2] mitigation in the short- to medium-term through the application of technological options. Despite the large potential, the energy usage and associated CO_2 emissions of the building stock in the EU continue to grow. Since turnover of the building stock is low in developed countries, the main opportunities for energy efficiency and GHG emission reduction arise from retrofitting the existing stock (Dineen and Ó Gallachóir, 2011). Thus, there has been a shift in focus from optimizing the efficiency of new buildings to efficiency measures that are applicable during the refurbishment process (Bradley and Kohler, 2007; Balaras et al., 2007). Nonetheless, much work remains to be done to assess systematically the potential and costs associated with applying energy saving measures (ESMs) for entire building stocks, e.g., the stock of an entire country (Ürge-Vorsatz et al., 2009; Kavgic et al., 2010). Such type of work requires both a description of the building stock and the development of modeling tools to assess the effects of ESMs. The work presented in this paper is part of a larger study (Pathways to Sustainable European Energy Systems; see Johnsson, 2011) and is developing a methodology for assessing ESMs for the European building stock.

The aim of the present study is to assess the effects of applying a set of ESMs to residential buildings in Sweden. In the 1990s, the investment costs and opportunities for energy efficiency in the Swedish building stock were calculated by the Swedish National

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[1] Industrialized countries agreed to reduce collectively their GHG emissions by 5.2% for the period 2008–2012, relative to their emission levels in 1990.

[2] As CO_2 is the most abundant GHG, the work in this paper considers CO_2 exclusively.

Council for Building Research, BFR [*Byggforskningsrådet* in Swedish] (1996). They used the MSA model (BFR, 1984, 1987) for residential buildings and the ERÅD model (Göransson et al., 1992) for commercial buildings. BFR (1996) also considered how the potential for ESMs could be achieved up to Year 2020, including new buildings that had yet to be built. However, these two models (MSA and ERÅD) are not readily available.

Current goals for the reduction of energy use in buildings in Sweden, as stated in the program of the Swedish Environmental Objectives Council [*Miljömålsrådet* in Swedish, cf. Boverket, 2007], are given as 20% less net energy usage per heated floor area by Year 2020, and 50% less consumption by Year 2050, both relative to the reference year of 1995. To begin to address these targets, the Swedish National Board of Housing, Building and Planning [*Boverket*, in Swedish] carried out in 2005 a field study (Boverket, 2009) that focused on the building stock in terms of energy usage, technology status, indoor air quality, and maintenance[3]. This study was facilitated by data from a high number of sample buildings, chosen as representative of the Swedish residential building stock. Some of the work presented in this paper was initially performed as part of a study commissioned by Boverket, which had the aim of evaluating net energy potential savings in the existing Swedish residential buildings, and those results have been published in part (Boverket, 2009, 2010). The work presented in the present paper advances the initial work (which was presented in Mata and Sasic Kalagasidis, 2009; Boverket, 2010) and has the following aims: a) to describe in detail the current energy usage of Swedish residential buildings; and b) to assess ESM with respect the technical energy savings associated with implementing the measures in the Swedish residential stock. In addition, the paper provides a brief comparison of the cost-effectiveness of the ESMs investigated. The assessment includes all end-uses, i.e., space heating, hot water, and electricity (for lighting, appliances, and cooking).

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[3] Further data on the survey is given in Section 2.2

The present paper starts with a brief description of the Swedish energy system and of energy usage in the residential stock, based on energy data from statistical databases. Thereafter, the information on the present Swedish stock (from statistical sources) is complemented with the results of the modeling, in which the building stock is characterized in detail (using the parameters of net energy, final energy, and CO_2 emissions), together with the data disaggregated into Single-Family Dwellings (SFDs) and Multi-Family Dwellings (MFDs). Finally, the paper presents technical potentials for energy savings and reduction of CO_2 emissions as identified from the modeling.

2. SWEDISH RESIDENTIAL BUILDING STOCK

The characteristics of the building stock in Sweden have been thoroughly mapped in various investigations conducted over the last 20 years. Although the energy usage of the Swedish building sector is just below the average value for the EU, associated CO_2 emissions are low owing to the characteristics of the Swedish energy system. With 46% of the electricity produced from hydro power and 45% from nuclear power, CO_2 emissions from electricity generation in Sweden are very low (Year 2005 data; Swedish Energy Agency, 2011). In addition, district heating, which accounts for 30% of the final energy of the building sector (Enerdata, 2010), is mostly produced from biomass and waste combustion (59%), heat pumps (12%), and waste heat (11%) (data for Year 2005; Swedish Energy Agency, 2011).

2.1. Energy usage in buildings

The Swedish residential sector accounts for 21% of the overall final energy use, a value that is slightly below the average of 26% for EU-27 countries (EC, 2011). This difference is attributable to: 1) the superior building envelopes used in northern European countries (Balaras et al., 2007), which mainly relates to the colder climate in these countries; and 2) the use of more efficient energy supply systems. Figure 1 shows that final energy use for the Swedish residential sector has remained almost constant over the past 20 years, while switching towards fuels with lower levels of CO_2 emissions has resulted in *decarbonization* of the Swedish building sector (as well as of the energy system in general).

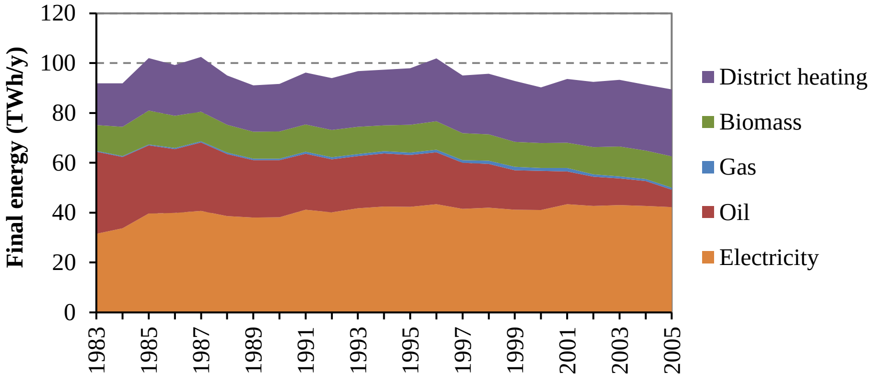

Figure 1. Final annual energy use by carrier over time for the Swedish residential sector in TWh/yr. Source: Enerdata(2010).

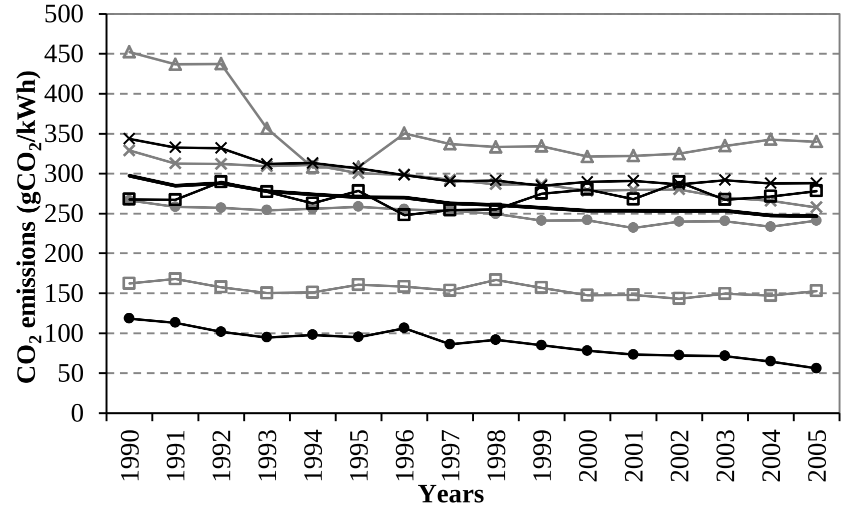

Figure 2. Evolution of *CO_2 emissions from the residential building sector*[4] (gCO_2/kWh) for selected European countries and the EU-27. Source: Enerdata (2010).

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[4] This is denoted "*Households' CO_2 emissions*" in Enerdata (2010).

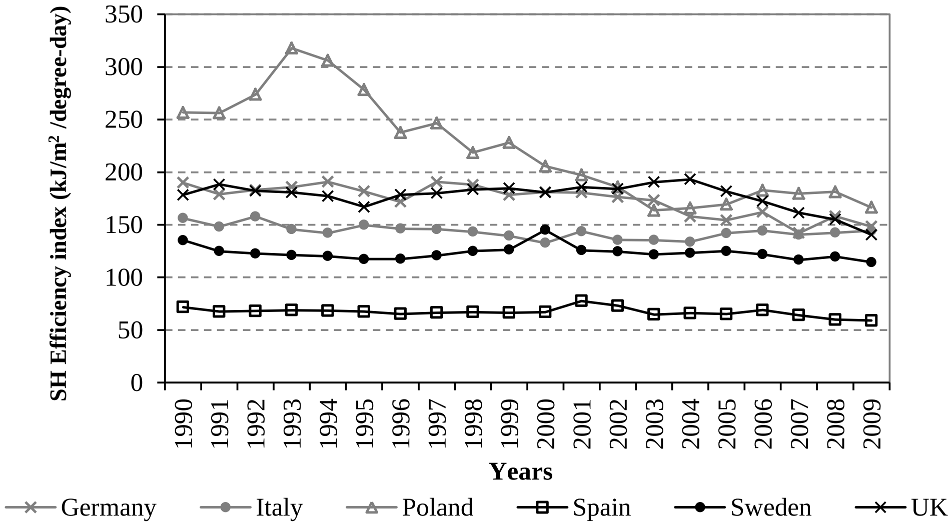

Figure 3. The space heating efficiency indicator with climatic corrections[5] (kJ/m^2/degree-day) for selected European countries[6]. Calculated from data provided by Enerdata (2010).

The levels of CO_2 emissions associated with the production of electricity and district heating, which are the energy carriers that account for the largest share of final energy use in the Swedish residential sector (Figure 1), are 15 gCO_2/kWh (based on a Swedish mix) and 70 gCO_2/kWh, respectively (Johnsson, 2011; Recyclingnet, 2012). These values are much lower than the average values for the EU-27 countries. Therefore, despite similar final levels in energy use, CO_2 emissions from the residential sector represent only 10% of the total CO_2 emissions in Sweden, while in the EU-27, the average share of for the residential sector in terms of total national CO_2 emissions is 22% (Enerdata, 2010) (see trends in Figure 2). In addition, CO_2 emissions from the Swedish residential sector have decreased faster than the overall emissions in the country, with buildings accounting for 18% of total emissions in 1990 and only 10% in 2005 (Enerdata, 2010). The reduction in carbon emissions is a result of decarbonization of the primary energy sources and a decrease in the energy delivered per floor area. (*cf.* Nässén and Holmberg, 2005).

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[5] The indicator has been calculated from the *Final consumption of residential for space heating with climatic corrections* and the *Degree-days of reference* in Enerdata (2010).

[6] The indicators for France and EU-27 could not be calculated due to the absence of data regarding the floor areas for these regions in Enerdata (2010).

In order to compare Sweden to other EU countries with different energy mixes, size of dwellings and outdoor climate, Figure 3 gives the energy delivered per floor area expressed by the indicator *space heating energy per unit floor area and per-degree day* (kJ/m^2/degree day). A low value of this indicator is generally a result of an efficient building envelope, an efficient heating system, low indoor temperatures or high outdoor temperatures, of which the first two apply to Swedish conditions, as pointed out in the beginning of the section. The low values for Spain are actually due to low indoor temperatures (in winter time). As can be seen in Figure 3, Sweden has one of the lowest usage of space heating energy (per unit floor area)[7]. Unlike the improvements in the energy efficiency of space heating in Germany and UK, Sweden shows only a weak improvement in energy efficiency that, to a large extent, can be attributed to upward trends in energy prices (Nässén et al., 2008).

2.2. Characterizing the building stock

Several investigations of the characteristics of Swedish buildings have been carried out, including the ERBOL, ELIB, and STIL2 studies. ERBOL (carried out in 1984–1985) was based on a survey that included about 1,500 housing units and offices in 62 Swedish municipalities (Tolstoy and Svennerstedt, 1984). ELIB (performed in 1993) inspected 1,148 selected buildings based on statistical criteria buildings in 60 municipalities, to gather data on technical characteristics, energy use, and indoor climate (SIB, 1993[8]). STIL2 (carried out in 2006) assessed the energy usage and indoor environment of schools and preschools in Sweden, and included a questionnaire on perceived indoor environment, which was filled out by the staff of 105 of these schools (Swedish Energy Agency, 2007).

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[7] Enerdata (2010) reports, for Year 2000, 3007 degree-days (DD) instead of 3855 normal degree-days of reference (DDn, calculated as the average annual DD of the period 1980-2004). The peak in year 2000 is linked to the combined effect from year 2000 being exceptionally warm and the choice of reference degree days rather than an actual increase in heating demand.

[8] This is the only report in English. A complete set of reports in Swedish is available at: http://www.boverket.se/Bygga--forvalta/sa-mar-vara-hus/om-undersokningen/Om-ELIB/

The present work is based on data from the most recent update of the residential stock, the so-called BETSI program (initiated in 2005) and described by Tolstoy (2011). As part of this program, 1,800 buildings (1,400 residential and 400 commercial buildings) were inspected; the buildings had been chosen by Boverket in cooperation with Statistics Sweden (SCB, 2008) as being 'statistically representative'[9] of the Swedish building stock. The data are divided into SFDs and MFDs and according to the year in which the buildings were built (i.e., before 1960, 1961–1975, 1976–1985, 1986–1995 or 1996–2005; categorized according to changes in regulation codes and building techniques). The buildings were chosen from 30 different municipalities according to population size and geographic location, so as to have a good representation of municipalities of different sizes and from different climatic regions. In all, there are 300 categories with different combinations of building type, age and location (Hjortsberg, 2011). The buildings were investigated by focusing on the current status of the building stock in terms of energy usage, technology status, indoor air quality, damage and maintenance. Energy audits were carried out by 50 inspectors. Through surveys and measurements, the inspectors collected data on the construction of the buildings (building year, type of foundation, roof, walls, and windows), building services (heating, ventilation, and water supply systems and equipment), and indoor air quality (indoor air temperature, relative humidity, and concentrations of radon and volatile organic compounds). In addition, tenants filled out a questionnaire on other issues such as related to personal health and perceived indoor air quality (see Boverket, 2009 for details).

From the BETSI project, a set of input parameters for the energy calculations was obtained, although other sources were also used to complement the inputs required for the modeling. Specifically the average power demand for hot water production, which is required in the model as an input (in W/m^2), is taken from the Swedish Energy Agency (2009). The

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[9] The meaning of the term *statistically representative* is not clear from the available reports (Boverket, 2009; Hjortsberg, 2011).

average electricity demand for lighting and appliances (in W/m^2) is assumed constant and equivalent to the average heat released to the indoor air, and is based on data from the Swedish Energy Agency (2011).

Table 1 lists the input parameters required for the modeling performed in this work, which include: building geometry; properties of the construction materials; energy characteristics of the subsystems; and the required indoor temperature.

Table 1. Model input parameters used to characterize the energy usage in each of the 1,400 buildings modeled in this work.

Description	Unit
Area of heated floor space	m^2
Total external surfaces of the building	m^2
Total window surface area of the building	m^2
Shading coefficient of the window	%
Frame coefficient of the window	%
Effective volumetric heat capacity of a heated space (whole building)	J/K
Coefficient of solar transmission of the window	%
Average U-value of the building envelope	W/m^2°C
Response capacity of the heating system	-
Maximum power rating of the heating system	W
Heat losses of the fan to the indoor air	W/m^2
Specific fan power	kW/m^3/s
Efficiency of the heat recovery system	%
Electricity consumption of hydro pumps	W/m^2
Minimum indoor temperature	°C
Indoor temperature above which opening windows/natural ventilation is assumed to occur	°C
Initial indoor temperature	°C
Minimum ventilation flow rate (sanitary ventilation)	l/s/m^2
Natural ventilation flow rate	l/s/m^2
Average constant heat gain due to people in the building	W/m^2
Average constant heat gain due to lighting and appliances in the building	W/m^2
Average power demand for hot water production	W/m^2
Location/ climatic zone	-

3. METHODOLOGY

3.1. Building stock model

The methodology uses a bottom-up engineering approach in which the net energy demand of individual buildings is calculated based on the physical and thermal properties of the buildings, the characteristics of the existing heating and ventilation systems, and climatic conditions. The model applied in this work is the ECCABS (Energy, Carbon and Costs

Assessment for Building Stocks) model developed by the authors and presented elsewhere (Mata et al., 2012). The model consists of two parts: a Simulink model, which solves the energy balance for buildings, and a provisional user interface written in Matlab (Mathworks, 2010), which handles the input and output data from the Simulink model. Unlike detailed building energy simulation models, which typically provide multi-zone and multi-layer specifications of the building and its envelope, the choice of spatial resolution of this model has been adjusted to the availability of input data and to the calculation time requirements. Therefore, each building is treated as one thermal zone with a thermal inertial described according to ISO 13790. At the same time, the model allows the calculation of indoor air temperature and a rather fine temporal (hourly-based) specification of the input data and the results. In this way, the model facilitates energy calculations for a large number of buildings and relatively large body of data required to describe a building stock. The model is applied to the 1,400 sample buildings described in Section 2.2., chosen as representative of the Swedish residential building stock.

The modeling applies a portfolio of technical ESMs that can reduce the energy demand (see Section 3.2). The results are then scaled-up to represent the entire stock. The calculated net energy for end-uses is converted into final energy (E_{final}) and CO_2 emissions using efficiency factors and carbon intensity factors for the fuels used. The potential reductions in energy use are calculated with respect to a so-called *baseline or reference year* (Year 2005 in the present work), which represents the current state of the existing building stock (energy usage in this baseline year is described in Section 4.1). The model can also calculate the costs related to the implementation of ESMs, and the measures are considered profitable when the cost of a new measure is lower than the cost of the energy that will be saved over the economic lifetime of the measure. If the calculation period is longer than a year (up to Year 2020 in the present work), the costs are discounted to the starting year. Further details on the costs are given in other work by the authors (Mata et al. 2010a, 2010b, 2011).

The meteorological data used in the modeling were generated by Meteonorm (Meteotest, 2009). The hourly values required in the model for the entire year are: outdoor temperature (ºC); global radiation on horizontal surfaces (W/m^2); diffuse radiation on horizontal surfaces (W/m^2); and normal direct radiation (W/m^2).

3.2. Energy saving measures studied

Twelve types of ESMs (outlined in Table 2) are assessed. Only ESMs that influence the net energy demand (E_{net}) are considered, since the specific energy targets of Swedish regulation are presented as net energy demand (*cf.* Section 1). Thus, ESMs that would affect the final energy level, such as fuel switching, have not been considered in the present work. The ESMs studied are:

- retrofit of the different parts of the envelope, i.e., basement, façade or roof (ESMs 1 to 3, respectively), and replacement of windows (ESM 4);
- use of ventilation systems with heat recovery for SFDs (ESM 5) and for MFDs (ESM 6);
- a reduction by 50% of the power required (the reduction is calculated with respect to the baseline year, 2005) for lighting and appliances (ESMs 7 and 8, respectively). The investment cost is considered to be zero, given that now there is no other alternative in Sweden than to buy equipment more efficient than the average equipment installed in existing buildings;
- reductions in the use of hot water for SFDs (ESM 9) and for MFDs (ESM 10) through substitution of existing water taps and WCs with aerator taps;
- reductions in the electrical consumption of hydro pumps (ESM 11) through the replacement of existing hydro pumps with more efficient ones;

- a reduction of the indoor temperature down to 20°C through the installation of thermostats (ESM 12). Measurements prove the average indoor temperature to be 21.2°C in SFD and 22.3°C in MFD (Boverket 2009) and these are also almost constant over the day during the heating period. The causes for such relatively high and constant indoor temperatures will be discussed in detail in Section 4.2.

The model assumes that the ESMs are applied to their full potential, which is of course a simplification. Some of the measures (e.g., ESMs 1–4) will mainly require replacement of a part of the building or its systems with a more energy-efficient component/system (and once this replacement is executed, no further action is required of the tenant). Thus, it can be assumed that the potential improvements will be fully achieved if the measure is applied, e.g., if the windows are replaced. However, most of the ESMs (e.g., ESMs 5–12) involve certain behavioral changes and adequate operation by the occupants of the newly installed technologies. Considerations on behavioral issues and rebound effects are outside the scope of this work, which has the aim to estimate the maximum technical potential for the ESMs.

The number of ESMs assessed in the present study is the result of grouping the 23 measures, suggested by Boverket during the above-mentioned co-operation within the BETSI program (cf. the detailed description of the 23 measures in Boverket, 2009 and Mattsson, 2011). It is, however, rare to have such detailed knowledge of the building stock based on sample buildings that allowed, for instance, to differentiate between several types of retrofitting strategies for cellars, facades and roofs. Thus, the amount of measures was decreased as to reduce the number of inputs required for modeling the ESMs. A validation of the reduction in the number of measures has been presented by Mata et al. (2010a). This validation involved comparisons of the resulting energy saving potentials and costs obtained for the 23 ESMs with those obtained for the 12 ESMs.

Table 2. Energy-saving measures (ESM) assessed in the present work

ESM	Description
1	Change in U-value of cellar/basement (different types)
2	Change in U-value of facades (different types)
3	Change in U-value of attics/roofs (different types)
4	Replacement of windows
5	Upgrade of ventilation systems with heat recovery, for SFDs
6	Upgrade of ventilation systems with heat recovery, for MFDs
7	Reduction by 50% of power for lighting
8	Reduction by 50% of power for appliances
9	Reduction in power used for the production of hot water to 0.80 W/m^2, for SFDs
10	Reduction in power used for the production of hot water to 1.10 W/m^2, for MFDs
11	Replacement of hydro pumps with more efficient ones
12	Lowering of indoor air temperature to 20°C

The costs applied consist of those of material and labor for work related to implementation of the ESMs, including taxes (i.e., consumer prices). Most of the actions are assumed to be implemented simultaneously, such as the renovation of facades and roofs, and therefore only the marginal or extra costs linked to the energy-saving requirements of the retrofitting measure are taken into account. The discount rate is set at 4% for all the measures (as suggested within BETSI project, *cf*. Mattsson, 2011). Details of the annual cost for each measure are provided in the publications by Mata et al. (2010a, 2010b, 2011).

The consumer energy prices (exclusive of VAT, but inclusive of all other taxes) for the period 2005–2007 are based on data from Göransson and Pettersson (2008). The estimated consumer energy prices for the period from 2008–2020 are taken from Profu (2008), which expanded the data of BRF (1996) to include the prices for electricity, district heating, oil, natural gas, and biomass.

The potential savings for the ESMs are calculated in two different ways: *individual* and *aggregated*. In the individual approach the measures are applied separately in the modeling, i.e., only one at a time, to obtain information of the potential energy saving from each measure. However, these potentials cannot be added together to obtain the overall effect of the measures. Thus in the aggregated case, the measures are applied simultaneously in the modeling, i.e., all at the same time, since the effects of one measure can influence other measures.

4. RESULTS

4.1. Energy demand of the Swedish residential building sector in Year 2005

Table 3 provides a summary of the net energy demand (E_{net}) of the Swedish residential stock, as obtained from the modeling methodology in the present study. For Year 2005, the E_{net} corresponds to 96.5TWh/yr, 72% of which is attributed to space heating (SH) demand, 10% to hot water (HW) demand, and 18% to electricity for lighting and appliances (LA) demand (including cooking). The annual specific net energy demand of an average SFD is 156 kWh/m^2 for SH, 16 kWh/m^2 for HW, and 30 kWh/m^2 for LA. The annual specific net energy demand of an average MFD is 96 kWh/m^2 for SH, 18 kWh/m^2 for HW, and 36 kWh/m^2 for LA. There is a lack of statistics with respect to data for net energy demand by end-uses, i.e. no basis for validation of these results. However, the accuracy of the energy balance model has been validated previously using comparative and empirical methods, as described by Mata et al. (2012).

Table 3. Net energy demand by end-use in the Swedish residential sector in Year 2005, as obtained from the present modeling work.

	SFD	MFD	All residential
Heated floor area (Mm^2)	301.15	236.60	537.76
Number of buildings (M)	1887.56	165.84	2053.39
Net energy demand by end-uses (TWh/yr)			
SH	47.1	22.7	69.8
HW	4.7	4.4	9.1
LA	9.2	8.4	17.6
Total	**61.0**	**35.5**	**96.5**

The size of the stock used in the present work was derived from the BETSI study and is expressed in *heated floor area* (referred to as A_{temp}, in m^2), i.e., the floor area to be heated to a temperature above 10ºC, limited by the inner side or the envelope. The BETSI study used A_{temp} because it is the measure used in the mandatory building codes, and it is also the measure used by the Swedish Environmental Objectives Council (EOC, 2009*)*. However, international statistics bodies most often list *residential floor area* (BOA, in m^2), which refers to the total area of the dwellings, excluding common areas (e.g., staircases) and the area occupied by walls. The issue of how area is defined is discussed in detail elsewhere (Boverket, 2009). It is important to be aware of the distinctions between the various definitions in order to understand any differences that may arise between the official statistics and the results of the present work, when comparing specific energy demands (discussed at the end of this section). The Odyssee and GAINS databases (Enerdata, 2010; IIASA, 2010) report a total residential BOA for the Swedish residential buildings of 370–390 Mm^2, and assign SFD/MFD ratios of 50%/50% (Odyssee) and 60%/40% (GAINS). The average floor area of an SFD is 160 m^2 and the average floor area of an MFD is 84 m^2 (Boverket, 2009), which gives an average floor area of 114 m^2 for a Swedish dwelling. In Table 3, the number of buildings does not necessarily correspond to the number of dwellings, as SFD may include some houses with two resident families, and an average MFD includes 17 dwellings (Boverket, 2009).

Table 4. Final energy demand (TWh/yr) by end-use in the Swedish residential sector in Year 2005, as obtained from the present modeling work.

All Residential	Electricity	Oil	Gas	Biomass	DH	Other	Total
SH	18.4	2.8	1.0	11.0	29.6	2.7	65.5
HW	2.4	0.3	0.2	0.9	4.7	0.3	8.8
Lighting	3.6						3.6
Appliances	14.1						14.1
TOTAL	38.4	3.1	1.2	11.9	34.2	2.9	91.8
SFD							
SH	16.5	2.2	0.3	10.8	11.2	2.3	43.3
HW	2.0	0.2	0.0	0.9	1.1	0.3	4.5
Lighting	1.9						1.9
Appliances	7.3						7.3
TOTAL	27.7	2.4	0.3	11.7	12.2	2.6	57.0
MFD							
SH	2.0	0.5	0.7	0.2	18.4	0.3	22.1
HW	0.4	0.1	0.2	0.0	3.6	0.0	4.3
Lighting	1.7						1.7
Appliances	6.8						6.8
TOTAL	10.7	0.6	0.9	0.2	22.0	0.4	34.8

Table 4 gives the modelled **final energy demand** (E_{final}) **in the baseline year 2005** for the Swedish residential building stock divided by end use. The E_{final} consists of 70% for SH demand, 10% for HW demand, and 20% for electricity for LA. The annual specific net energy demand of an average SFD is 144 kWh/m^2 for SH, 15 kWh/m^2 for HW, and 30 kWh/m^2 for LA and the corresponding figures for an average MFD are 94 kWh/m^2 for SH, 18 kWh/m^2 for HW, and 36 kWh/m^2 for LA.

The energy delivered for heat (SH+HW, 80% in the present work) agrees with the available statistics (81% for Sweden in Enerdata, 2010) and with the average of 82% reported for the EU (Pérez-Lombard et al., 2008). However, there is some discrepancy regarding the percentage of final energy for HW when comparing the results of the present work (10%) with the 23% reported for Sweden by Enerdata (2010). To investigate the reason for this difference, we looked at the final energy for SH and for HW distributed by fuel, as obtained in the present work (Fig. 4). In Swedish SFDs, more than 50% of the SH demand is supplied by electricity (via direct heating, electric boilers, and heat pumps), while DH and biomass together contribute 25% and oil and other fuels together contribute 5% of the SH demand. The percentages for HW demand are similar. In MFDs, both the SH and HW demands are met almost entirely by district heating.

The fuel shares derived in the present work for the overall residential stock, as shown in Figure 4, are not in complete agreement with those reported in the literature. For example, Enerdata (2010) reports SH shares for electricity, oil, biomass, and district heating of 37%, 10%, 18%, and 34%, respectively, as compared with the corresponding shares of 28%, 2%, 17%, and 45%, respectively, found in the present work. For HW, Enerdata reports shares for electricity, oil, biomass, and district heating of 29%, 10%, 15% and 46%, respectively, as compared to the corresponding shares of 27%, 3%, 10%, and 54%, respectively, in the present work. A possible reason for the discrepancies between the Enerdata values and those of the present study is that the data we used for HW demand (42 L/d per person in SFDs, and 58 L/d per person in MFDs) are based on a recent study in which it was shown that the use of HW in Swedish households (Swedish Energy Agency, 2009) was lower than previously reported. In SFDs, 33% of the total water volume used was HW, and in MFDs, 32% of the total water volume used was HW.

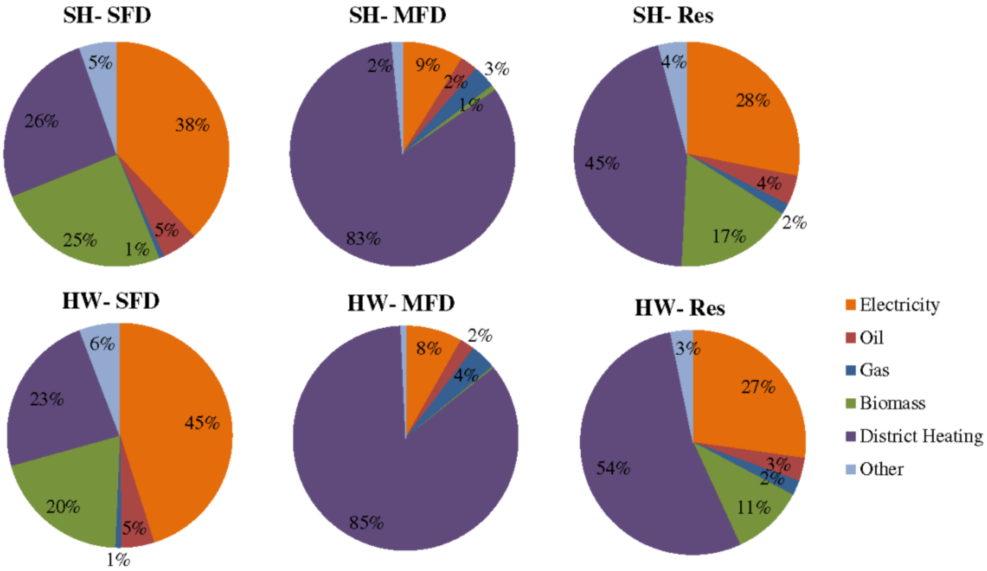

Figure 4. Final energy demand by fuel per end-use, as obtained from the modeling of the present work (upper panel, SH demand; lower panel, HW demand) for the Swedish residential stock. Results are shown for SFDs (left), MFDs (middle), and as the average for the overall residential stock (Res; right).

Some studies for other countries have reported HW usage levels that are higher than those calculated in the present study, e.g., 200 L/d per person in the USA (EM&RS, 1994), 68–92 L/d per person in Russia, and about 85 L/d per person in Finland (Koiv and Toode, 2006). However, other studies have reported values similar to those obtained in the present study, e.g., 46–85 L/d per person for residential homes in the USA (NAHB, 2002; reviewing sources that date from 1987 to 1998), 44 L/d per person in Estonia (Koiv and Toode, 2006), and 50 L/d per person in the UK (DEFRA, 2008). In general, the usage for a specific country reported from the above-mentioned sources tend to be higher the older the data, confirming a decrease in domestic HW consumption as a result of the increasing application of ESMs, such as the implementation of systems for measuring and billing consumption, renovation of domestic HW systems, and installation of low-flow taps and showers (Bohm and Danning, 2004; Koiv and Toode, 2006). In summary, the low level of HW usage assumed in the present work (from the Swedish Energy Agency, 2009) is the reason for the differences in the percentages of final energy for HW, i.e., 10% in the present study versus the 23% reported for Sweden by Enerdata (2010).

The **annual specific final energy demand in Year 2005** of the Swedish residential stock, as assessed in the present work, is 171 kWh/m^2, which can be subdivided as follows: 122 kWh/m^2 for SH; 16 kWh/m^2 for HW; 7 kWh/m^2 for lighting; and 26 kWh/m^2 for appliances (including cooking). For SFDs, the annual specific final energy demand is 189 kWh/m^2, which can be subdivided as follows: 144 kWh/m^2 for SH; 15 kWh/m^2 for HW; 6 kWh/m^2 for lighting; and 24 kWh/m^2 for appliances (including cooking). For MFDs, the annual specific final energy demand is 148 kWh/m^2, with 94 kWh/m^2 for SH, 18 kWh/m^2 for HW, 7 kWh/m^2 for lighting, and 29 kWh/m^2 for appliances (including cooking). Thus, on average, an SFD requires more energy for SH, while an MFD generally requires more energy for HW and LA.

4.2. Technical potential for energy savings

Table 5 lists the technical energy saving potentials (TWh/yr) as obtained from the application of the modeling methodology to the existing Swedish building stock. The total annual energy demand of the sector can be reduced by 51.0 TWh/yr (53%) by applying all the ESMs aggregated. Table 5 also shows the results from applying the ESMs on an individual basis (cf. Section 3.2). The different ESMs generate savings of between 0.3 TWh/yr and 13.3 TWh/yr. The measures that provide the greatest savings are those that involve heat recovery systems and a reduction of the indoor temperature, which each provide 9-13 TWh/yr. The upgrading of the U-value of cellar/basement and of facades (different types), and the replacement of windows each provide a saving of 5-7 TWh/yr. These potential savings are calculated on the assumption that there are no changes in the energy systems with respect to the efficiencies of the different energy carriers. As pointed out previously, the energy savings reported here are the maximum potentials which can be obtained by the application of the ESMs.

Table 5 also shows which part of the potential for each ESMs is cost-effective (i.e. which will result in an economical gain). For further discussions on cost-effectiveness, see other work by the authors (Mata et al. 2010a, 2010b and 2011).

Table 5. Technical energy saving potentials (TWh/yr) and the amount of these which are cost effective, as obtained from the modeling in the present study.

ESM	Description	Individual	Aggregated	Cost-effective part
1	Change in U-value of cellar/basement (different types)	5.3	4.3	0.3
2	Change in U-value of facades (different types)	7.2	5.7	0.2
3	Change in U-value of attics/roofs (different types)	2.7	2.2	0.9
4	Replacement of windows	6.5	5.3	0.9
5	Upgrade of ventilation systems with heat recovery, for SFDs	12.0	9.2	5.3
6	Upgrade of ventilation systems with heat recovery, for MFDs	9.6	8.0	0.2
7	Reduction by 50% of power for lighting	0.3	0.3	0.3
8	Reduction by 50% of power for appliances	1.0	1.0	0.9
9	Reduction in power used for the production of hot water to 0.80 W/m^2, for SFDs	2.6	2.1	0.9
10	Reduction in power used for the production of hot water to 1.10 W/m^2, for MFDs	2.1	1.8	0.1
11	Replacement of hydro pumps by more efficient ones	0.6	0.5	0.2
12	Decrease in indoor air temperature to 20°C	13.3	10.6	13.1
	Total	**63.2**	**51.0**	**23.5**

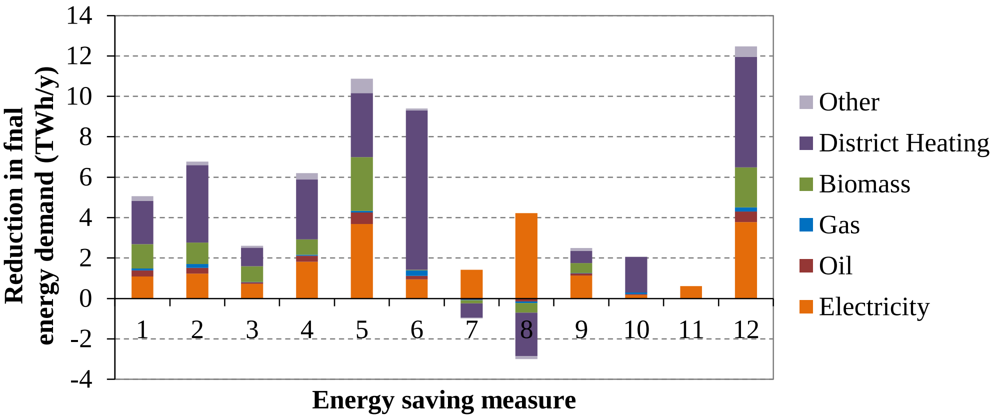

Figure 5. Level of reduction in final energy demand by fuel (TWh/yr, *y*-axis) for each of the ESMs studied (*x*-axis) for the Swedish residential stock, as a result of the present modeling work. The ESMs are represented by numbers; a detailed description of each measure is provided in Table 2.

Figure 5 gives the energy saved by fuel (TWh/yr) for the ESMs when applied individually, and Table 6 assigns these data to the subcategories of SH, HW, and LA. For those measures that only affect demand for SH (ESMs 1–4, 12), the fuel distribution in Figure 5 corresponds to the average fuel mixes for SH of the dwellings in which the measure can be applied. ESM 5 and 6 increase electricity consumption. However, the increase is smaller than the saving in SH, which is provided partially by electricity (38% in SFDs and 9% in MFDs; Figure 4). When the electricity demand for lighting and appliances is reduced (ESMs 7 and 8), so is the heat released by the lights and appliances to the indoor air; thus, the demand for SH increases (i.e., the negative values in Figure 5). However, the application of ESM 7 and ESM 8 results in overall energy savings, as evident from Table 6.

Table 6. Effects of the application of ESMs on the net energy by end-use in the Swedish residential sector (TWh/yr), as obtained using the modeling methodology of the present work. The ESMs are represented by numbers; a detailed description of each measure is provided in Table 2.

Measure		SFD	MFD	Residential
1	SH	3.71	1.62	5.33
	HW	0	0	0
	LA	0	0	0
	Total	**3.71**	**1.62**	**5.33**
2	SH	4.97	2.24	7.21
	HW	0	0	0
	LA	0	0	0
	Total	**4.97**	**2.24**	**7.21**
3	SH	1.96	0.72	2.68
	HW	0	0	0
	LA	0	0	0
	Total	**1.96**	**0.72**	**2.68**
4	SH	4.06	2.45	6.51
	HW	0	0	0
	LA	0	0	0
	Total	**4.06**	**2.45**	**6.51**
5	SH	12.74	0	12.74
	HW	0	0	0
	LA	-0.78	0	-0.78
	Total	**11.95**	**0**	**11.95**
6	SH	0	9.36	9.36
	HW	0	0	0
	LA	0	0.25	0.25
	Total	**0**	**9.61**	**9.61**
7	SH	-0.79	-0.65	-1.44
	HW	0	0	0
	LA	0.95	0.83	1.78
	Total	**0.16**	**0.18**	**0.34**
8	SH	-2.39	-1.97	-4.35
	HW	0	0	0
	LA	2.84	2.48	5.31
	Total	**0.45**	**0.51**	**0.96**
9	SH	0	0	0
	HW	2.61	0	2.61
	LA	0	0	0
	Total	**2.61**	**0**	**2.61**
10	SH	0	0	0
	HW	0	2.11	2.11
	LA	0	0	0
	Total	**0**	**2.11**	**2.11**
11	SH	0	0	0
	HW	0	0	0
	LA	0.42	0.19	0.61
	Total	**0.42**	**0.19**	**0.61**
12	SH	8.96	4.13	13.09
	HW	0	0	0
	LA	0.22	0	0.22
	Total	**9.18**	**4.13**	**13.32**

Several aspects of the calculations of the energy savings potentials are discussed below.

Issues related to the baseline

With regard to the baseline: it should be noted that the modeling methodology (presented in Section 3.1) relates the energy efficiency measures to a baseline-year energy usage and that the climate data used in the simulations correspond to average values for 1995–2005, while the energy measurements (derived from field measurements and statistics) are for Year 2005. Since the aim is to estimate the potential energy savings, the accuracy of the baseline data should not be decisive, whereas results compared to any baseline are valid as long as the climate data and overall assumptions are similar. In addition, it has been assumed that the weather in the future will be identical to the above-mentioned average weather, which means that any effects of climate change on the energy use of buildings have not been considered (cf. Moussavi Nik, 2012 for a study of the impact of climate change on the energy performance of buildings in Stockholm).

A second baseline-related issue is the ventilation rates. The final energy demand of the Swedish residential building stock in Year 2005 was 91.8 TWh/yr (Table 4), obtained using the ventilation rates from the BETSI project. However, the values used as the input for the modeling of SFDs were lower than the 0.35 L/s/m^2 recommended by the Swedish Ministry of Health as the level needed to ensure adequate indoor air quality (Boverket, 2009). If the ventilation rate in the modeling of the SFDs is increased to 0.35 L/s/m^2, the demand increases to 97.7 TWh/yr. As it is reasonable to assume that adequate indoor air quality will be a requirement in the future, the energy demand for increased ventilation has been used as a baseline value to compare the potential energy savings presented in this section.

Issues related to the application of ESMs

Regarding application of the ESMs assessed in the present work, the first noteworthy issue is that the measures are applied all at the same time (as explained in Section 3.2) or individually but this latter only to compare as a reference. Other groupings of the measures, either for technical or operational reasons, have not been considered, although, for instance, it may be reasonable to replace the windows and at the same time check the envelope for air leakages. It may also be reasonable to retrofit the envelope before installing a ventilation system with heat-recovery. However, it might be easier for a building owner to switch from a private boiler to district heating rather than retrofit the envelope. More work is required to investigate alternative groupings of the ESMs.

Other application-related issues with respect to the different ESMs are worth discussion. The indoor temperatures in Swedish households are relatively high and constant several due to several reasons, namely: that district heating provides a constant temperature during the day (and the share of centrally heated buildings is much higher than in other countries); that the outdoor temperature in winter is rather stable due to low solar radiation; and that the buildings have good insulation and air-tightness (compared to other regions). However, it is a well-known fact is that decreasing the indoor temperature, despite its great potential for energy savings, is difficult to implement in less energy-efficient houses in which the increased air temperature compensates for other factors in the operative temperature (i.e., high air velocity due to infiltrations or low radiation temperatures from the envelope surfaces). Glad (2012) has provided some insights into how occupants experience the installation of thermostats, and concluded that occupants did not use them as intended, which lowered performance and also increased occupants' dissatisfaction. It is quite common for Swedish dwellings to be equipped with mechanical ventilation systems, especially in multi-family dwellings. As a result, it is relatively easy to replace the existing exhaust-only system by a heat-recovery system. However, the installation of heat recovery systems usually requires an improvement of the air-tightness of the building envelope (which has not been taken into account in this work, as mentioned above) in order to fully utilize its efficiency.

Thus, the results presented in this paper depend on the singularities of the building stock and the characteristics energy system of the region under investigation (Sweden).

As indicated, the present work gives the maximum technical potential saving which can be obtained from applying the ESMs investigated. Thus, the effect of some of the measures investigated may be reduced due to rebound effects. There are obviously several other factors which decide which measures will eventually be implemented and what will be the real energy saving. For instance the retrofitting of the envelope may increase indoor temperatures and the installation of more efficient appliances may be offset by an increase in the amount of such equipment. It is also known that homeowners are more likely to replace their windows than to renovate the facades, even if they know that insulating the facades has a greater impact in reducing the energy demand (Nair et al. 2010).

The model results for the Swedish case have been compared to the results of previous studies published on the topic. However, such comparisons are not straightforward, since the assumptions, ESMs options, and approaches used in the modeling process differ across the studies. First, there are several definitions of *energy saving potentials* and in Sweden the definitions are generally related to the so-called *cost savings*[10]. Our resulting total *technical potential*[11] is up to 65% higher than that reported by other sources (Sandberg, 2007), while our calculated *techno-economic potential*[12] saving is 10%–50% lower than that reported by BFR (1996), Dalenbäck et al. (2005), and Göransson and Pettersson (2008). Second, bottom-up modeling approaches generally tend to provide higher resulting potentials than top-down assessments (see Swan and Ugursal, 2009). Third, the number of measures studied of course

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[10] *Cost savings* are defined as the sum of the investment and the present value of the annual maintenance cost of the ESMs, divided by the present value of the cost of the annual energy savings (GB, 1977). These savings were used as the basis for the first Swedish energy-saving plan and have subsequently been used in all Swedish energy efficiency assessments.

[11] The *technical potential* is defined as the amount by which it is possible to reduce energy demand or CO_2 emissions by implementing already-demonstrated technologies and practices without specific reference to costs. Thus, it corresponds to the individual and aggregated potentials given in this paper, e.g. in two middle columns of Table 5.

[12] The *techno-economic potential* is the cost-effective (i.e., profitable) technical potential to reduce energy demand or CO_2 emissions, as shown in the rightmost column of Table 5.

influences the total potential (e.g., some studies do not include reduced indoor temperature as an efficiency option). Fourth, the choice of data used for the description of the building stock also affects the results.

Sandberg (2007) reported a technical potential of 33.7 TWh/yr (versus 51.0 TWh/yr in the present study). However, Sandberg used a top-down model and applied measures different from those used in the present work (e.g., reduced indoor temperature was not included). BFR (1996) reported a techno-economic potential savings in the range of 30–45 TWh/yr, depending on the assumptions made (versus 23.5 TWh/yr in the present study). Dalenbäck et al. (2005) updated the energy prices and assumptions from BFR and reported a total potential techno-economic saving of 26.0 TWh/yr, while Göransson and Pettersson (2008), in updating once again the energy prices and assumptions, reported a total potential techno-economic saving of 41.0 TWh/yr. These three studies have all applied the previously mentioned cost savings (GB, 1977) and used an interest rate that is different from the one used in the present work (6% versus 4%, respectively). In addition, their studies are based on the description of the Swedish buildings as they were in Year 1995 (Boverket, 1995), while the present work is based on the Swedish buildings as they were in Year 2005.

4.3. Carbon dioxide emissions of the Swedish residential stock

Table 7 shows that the **annual CO_2 emissions in Year 2005** from the Swedish residential stock were 4.92 $MtCO_2$, of which 2.62 $MtCO_2$ were attributed to SFDs and 2.29 $MtCO_2$ to MFDs. This represents 10% of the 47.0 $MtCO_2$ reported as the total annual emissions of the country (Enerdata, 2010). Enerdata (2010) does not report statistics for the residential sector that can be directly compared to the results obtained in the present study. Table 7 also includes the detailed shares by fuel. The largest potential for further reductions in the CO_2 emissions lies in DH, which now accounts for almost 50% of the CO_2 emissions of the residential sector, despite the fact that it accounts for only 37% of the sector´s final energy demand (see Table 4). According to the results, an average Swedish SFD emits 1.39 tCO_2/yr, while an average Swedish MFD emits 0.81 tCO_2/yr and an average residential dwelling emits 1.05 tCO_2/yr.

Table 7. Results of CO_2 emissions ($MtCO_2$/yr) by fuel in the Swedish residential sector for Year 2005, based on the results of the current work.

Fuels	SFD	MFD	Residential
Electricity	0.41	0.16	0.57
Oil	0.66	0.17	0.83
Gas	0.13	0.36	0.49
Biomass	0.12	0	0.12
Coal	0	0	0
DH	0.86	1.54	2.40
Total	2.62	2.29	4.92

The literature does not provide any data on CO_2 emissions disaggregated into SFDs and MFDs, which could be compared to the results obtained in the present work. However, data on the overall residential stock are provided by Enerdata (2010), which reports CO_2 emissions of 4.77 $MtCO_2$, and by the Swedish Energy Agency (2011), reporting CO_2 emissions of 5.32 $MtCO_2$. These results are similar to the 4.92 $MtCO_2$ of CO_2 emissions uncovered in the present work. As already noted, if other GHGs are included, this value would increase. For instance, the total annual GHG emissions for Sweden are 67.7 $MtCOe_2$ (EC 2011), which is 44% higher than the above-reported level of emissions, which only considers CO_2 (47.0 $MtCO_2$). Current work by the authors investigates how to include all GHG emissions; the main problem with this task is that data on all the GHG emissions related to the production of the different fuels are lacking.

The total **potential for CO_2 emission reduction**, as obtained from the current modeling, is 2.9 $MtCO_2$/yr, which represents 63% of the emissions from the Swedish building sector. Carbon intensities for the fuels are assumed to be constant over the years. However, the obtained potential for CO_2 emission reduction may not be relevant in an overall strategy for the country, since the CO_2 emissions of the residential sector represent only 10% of the total emissions in Sweden. Obviously, there are other EU countries in which the building sector can contribute greatly to reducing CO_2 emissions (e.g., the UK and Poland), i.e., for which an assessment similar to that conducted in the present work should be of high value. It should be noted that in terms of CO_2, the application of ESM 7 and ESM 8 increases CO_2 emissions, given that the electricity saved has lower levels of emissions associated with its production than the fuel mix used for space heating. Such an effect is evident in Figure 6, where the potential reductions in CO_2 emissions and final energy are given as percentages of the baseline and for the ESMs studied for the Swedish residential stock. Therefore, it is important to assess ESMs both in terms of energy and CO_2 emissions.

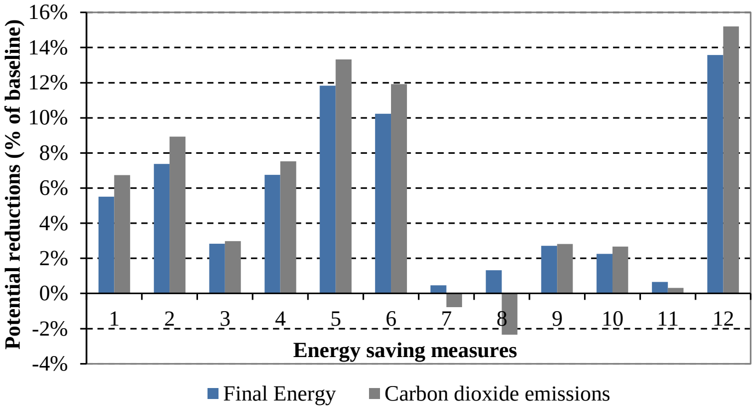

Figure 6. Potential reductions in final energy and CO_2 emissions, given as percentages of the baseline (*y*-axis) for each of the ESMs studied (*x*-axis) for the Swedish residential stock, as obtained in the present work. The ESMs are indicated by number; detailed descriptions of the measure are provided in Table 2.

5. CONCLUSIONS

The current energy use of the Swedish residential building stock (represented by 1,400 sample buildings) is presented with respect to size (number of buildings and areas), energy use (net energy and final energy by fuels), and associated CO_2 emissions to which a number of energy saving measures (ESMs) is applied. The results are disaggregated for SFDs and MFDs.

It is shown that application of the selected ESMs has the potential to reduce the final energy demand of the Swedish residential sector by 53%. The measures that provide the greatest savings are those that involve heat recovery systems and those that involve a reduction of the indoor temperature, giving energy savings of 22% and 14%, respectively. Upgrading the U-values of the building envelope and windows would each provide annual energy savings of 7%. These results are average values for Sweden, which means that before policy or investment decisions are taken at any other organizational level other than the national one, the results should be examined in greater detail. The modeling outcomes could also be scrutinized for each climatic region and for different types of buildings. In addition, the above-listed potentials are to be seen as technical maximums, and further work is needed to clarify how these potentials could be achieved and to identify a robust approach to implementing these measures.

The level of CO_2 emissions from the Swedish building sector could be reduced by 63% by applying all the ESMs studied. However, the levels of emissions from the Swedish building sector are already low (10% of the total emissions for the country), and allocating the costs of the ESMs to reduce CO_2 emissions gives high abatement costs (per ton CO_2-avoided). Therefore, emission reduction is not likely to provide the main impetus for imposing energy efficiency measures. Rather, the profits gained from energy efficiency measures and indirect effects, such as reduced dependency on electricity (which may give indirect reductions in terms of CO_2 emissions), are strong motivations for implementing the ESMs.

Although the application of the ESM would generally reduce CO_2 emissions, the measures that would reduce electricity use for lighting and appliances would increase CO_2 emissions because the saved electricity production is less-CO_2-intensive than the fuel mix used for space heating. Therefore, it is not recommended to take decisions based solely on energy or CO_2 assessments. At the same time, one should look at the implications of the

ESMs in terms of final energy for the entire energy system.

REFERENCES

Balaras, C.A., Droutsa, K., Dascalaki, E., Kontoyiannidis, S., 2005. Heating energy consumption and resulting environmental impact of European apartment buildings. Energy and Buildings, 37 (5), 429-42.

Balaras, C.A., Gaglia, A.G., Georgopoulou, E., Mirasgedis, S., Sarafidis, Y., Lalas, D.P., 2007. European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. Building and Environment, 42 (3), 1298-1314.

BFR, 1984. Energi 85 Energianvändning i bebyggelse G26:1984 (in Swedish). Byggforskningsrådet (BFR). Stockholm, Sweden.

BFR, 1987. Energi i byggd miljö, 90 talets möjligheter G16:1987 (in Swedish). Byggforskningsrådet (BFR). Stockholm, Sweden.

BFR, 1996. Energieffektivisering. Sparmöjligheter och investeringar för el- och värmeåtgarder i bostäder och lokaler, Anslagsrapport A1:1996 (in Swedish). Byggforskningsrådet (BFR). Stockholm, Sweden.

Bohm, B., Danning, P.O., 2004. Monitoring the energy consumption in a district heated apartment building in Copenhagen, with specific interest in the thermodynamic performance. Energy and Buildings, 36, 229-236.

Boverket, 1995. ELIB - Elhushållning i bebyggelsen (in Swedish). Karlskrona, Sweden.

Boverket, 2005. Piska och Morot, Boverkets utredning om styrmedel för energieffektivisering i byggnader (in Swedish). Karlskrona, Sweden.

Boverket, 2007. Bygg- och fastighetssektorns miljöarbete - Rapport om särskilt sektorsansvar för miljömålsarbete 2007 (in Swedish). Karlskrona, Sweden.

Boverket, 2009. Så mår våra hus. Redovisning av regeringsuppdrag beträffande byggnaders tekniska utformning m.m. (in Swedish). Karlskrona, Sweden.

Boverket, 2010. Energi i bebyggelsen – tekniska egenskaper och beräkningar. Resultat från projektet BETSI (in Swedish). Karlskrona, Sweden.

Bradley, P. E., Kohler, N., 2007. Methodology for the survival analysis of urban building stocks. Building Research & Information, 35(5), 529- 542.

Dalenbäck J. O., Görasson A., Lennart J., Nilson A., Olsson D., Pettersson B., 2005. Åtgärder för ökaden energieffektivisering I bebyggelse. Report CEC 2005:1 (in Swedish). Chalmers Energi Centrum , Chalmers University of Technology, Gothenburg, Sweden.

DEFRA, 2008. Measurement of domestic hot water consumption in dwellings. Department for Environment, Food and Rural Affairs (DEFRA).

Dineen D. and Ó Gallachóir B.P, 2011. Modelling the impacts of building regulations and a property bubble on residential space and water heating. Energy and Buildings, 43 (1), 166-178.

EC, 2011. Eurostat Database. European Commission (EC), Brussels, Belgium.

EM&RS, 1994. Energy use and domestic hot water consumption. Final Report Phase 1 Prepared for the New York State energy research and development authority. Energy Management & Research Associates (EM&RS), New York.

Enerdata, 2010. ODYSSEE database European Energy Efficiency Indicators NRDLINK 4.1 (SP1). Grenoble, France.

Energidata, 1989. The Model ERÅD - A documentation (In Norwegian).

ESRU, 2010. ESP-r, Version 11.3. Energy Systems Research Unit, University of Strathclyde, Glasgow, Scotland.

GB, 1977. Government bill, 1977/78:76: Energy saving program for existing buildings (In Swedish: *Regeringspropositionen 1977/78:76 Energisparplanförbefintligbebyggelse*), Stockholm, Sweden.

Glad, W., 2012. Housing renovation and energy systems: the need for social learning. Building Research & Information, 40 (3), 274-289.

Göransson, A., Lindahl, U., Forsman, G., Hedenström, C., 1992. Localerna och energihushållningen – Rapport från STIL-studien inom Uppdrag 2000. FUD-rapport U 1991/70 (in Swedish).Vattenfall Utveckling AB, Älvkarleby.

Göransson, A., Pettersson, P., 2008. Energieffektiviseringspotential i bostäder och lokaler. Med fokuspåeffektiviseringsåtgärder 2005 – 2016. Report - CEC 2008:3 (in Swedish). Chalmers Energi Centrum, Chalmers University of Technology, Gothenburg, Sweden.

Hjortsberg, M. Description of the Swedish building stock using material Swedish statistical survey of 1800 buildings, Swedish National Board of Housing, Building and Planning. Available at: http://www.boverket.se/Global/Om_Boverket/Dokument/about_boverket/betsi_study/building_stock.pdf

IEA, 1997. Indicators of energy use and efficiency. Understanding the link between energy and human activity. IEA/OECD, Paris, France.

IIASA, 2010. Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) database. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

IPCC, 2007. Summary for Policymakers. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz,O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer. (Eds).,Cambridge University Press, Cambridge, UK and New York.

ISO 13790, Energy performance of buildings - Calculation of energy use for space heating and cooling, 2008.

Johnsson, F. (Ed.), 2011. European Pathways - Pathways to Sustainable European Energy Systems. Chalmers University of Technology, Gothenburg, Sweden.

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., Djurovic-Petrovic, M., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. Building and Environment, 45, 1683-1697.

Koiv, T.A., Toode, A., 2006. Trends in domestic hot water consumption in Estonian apartment buildings, in: Proceedings Estonian Acad. Sci. Eng., 12, 1, 72–80.

Mata, É. et al., A modelling strategy for energy, carbon, and cost assessments of building stocks, Energy and Buildings (2012a), http://dx.doi.org/10.1016/j.enbuild.2012.09.037

Mata, É., Sasic Kalagasidis, A., 2009. Calculation of the energy use in the Swedish housing. Description of the building energy simulation model: EABS Energy Assessment of Building Stocks, Report 2009:4. Chalmers University of Technology, Gothenburg, Sweden.

Mata, É., Sasic, A., Johnsson, F., 2010a. Assessment of retrofit measures for reduced energy use in residential building stocks – Simplified costs calculation. Sustainable Building Conference SB10mad April 28-30, Madrid, Spain.

Mata, É., Sasic, A., Johnsson, F., 2010b. Retrofitting measures for energy savings in the Swedish residential building stock – assessing methodology, Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference December 5-9, Florida, USA.

Mata, É., Sasic, A., Johnsson, F., 2011. Costs of retrofit measures in the Swedish residential building stock – an evaluation for three scenarios on future energy prices. 9th Nordic Symposium on Building Physics. 29th May - 2nd June 2011 Tampere, Finland.

Mata, É., Sasic, A., Johnsson, F., 2012b. Cost-effective potentials for retrofitting the Swedish residential stock – Effects of energy price developments and interest rates. Submitted for publication.

MathWorks, 2010. MATLAB r2008a. The MathWorks, Inc., Natick, Massachusetts, U.S.A.

Mattsson, B. Costs for reducing the energy demand in the Swedish building stock according to national energy targets, Swedish National Board of Housing, Building and Planning. Available at: http://www.boverket.se/Global/Om_Boverket/Dokument/about_boverket/betsi_study/energy.pdf

Meteotest, 2009. Meteonorm Version 6, Global Meteorological Database for Engineers, Planners and Education. Bern, Switzerland.

Moussavi Nik, V., Sasic Kalgasidis, A., Impact study of the Climate Change on the Energy Performance of the Building Stock in Stockholm Considering Four Climate Uncertainties, Building and Environment (2012), http://dx.doi.org/10.1016/j.buildenv.2012.11.005

NAHB, 2002. Domestic Hot Water System Modeling for the Design of Energy Efficient Systems. NAHB Research Center, USA.

Nair, G. et al., 2010. Owners perception on the adoption of building envelope energy efficiency measures in Swedish detached houses, Applied Energy, 87 (7), 2411‑2419.

Nässén, J., Holmberg, J., 2005. Energy efficiency—a forgotten goal in the Swedish building sector?. Energy Policy, 33 (8), 1037–1051.

Nässén, J., Sprei, F., Holmberg, J., 2008. Stagnating energy efficiency in the Swedish building sector – Economic and organisational explanations. Energy Policy, 36 (10), 3814–22.

Pérez-Lombard, L., Ortiz J., Pout, C., 2008. A review on buildings energy consumption information. Energy and Buildings, 40 (3), 394–398.

Profu, 2008. Energieffektivisering i bebyggelsen, Analyser utifrån samhällsekonomiska och beslutsfattar-ekonomiska metoder (in Swedish). Mölndal, Sweden.

Recyclingnet, 2012.http://www.recyclingnet.se/artiklar/nyheter/fjarrvarmens-klimatpaverkan-minskar-ytterligare/ (in Swedish). [Link checked 7 July 2012]

Sandberg, E., 2007. Energieffektiva åtgärder vid renovering och utbyte. ATON teknikkonsult AB. Stockholm, Sweden (in Swedish).

SCB, 2008. www.scb.se/. Statistics Sweden [*Statistiska centralbyrån* (SCB), in Swedish]. Stockholm, Sweden.

SIB, 1993. The indoor climate in the Swedish housing stock. Norlen, U., Andersson, K. (Eds), Swedish Institute for Building Research [*Statens institut för byggnadsforskning* (SIB), in Swedish]. Gävle, Sweden.

Swan, L.G., Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, 13 (8), 1819-35.

Swedish Energy Agency, 2007. Energianvändning & innemiljö i skolor och förskolor – Förbättrad statistik i lokaler, STIL2, ER 2007:11 (in Swedish). Boverket och Swedish Energy Agency, Sweden.

Swedish Energy Agency, 2009. Mätning av kall- och varmvattenanvändning i 44 hushåll - Delrapport i Swedish Energy Agencyens projekt Förbättrad energistatistik i bebyggelsen och industrin, ER 2009:26 (in Swedish) . Eskilstuna, Sweden .

Swedish Energy Agency, 2011. Facts and figures- Energy in Sweden 2011. Eskilstuna, Sweden.

Tolstoy, N. Method to describe the technical characteristics of the existing buildings. A Swedish survey of 1800 buildings. Swedish National Board of Housing, Building and Planning. Available at:

http://www.boverket.se/Global/Om_Boverket/Dokument/about_boverket/betsi_study/method_descriptions.pdf

Tolstoy, N., Borgstrom, M., Hogberg, H., Nilsson, J., 1993. TN:29 Bostadsbeståmdets tekniska egenskaper ELlB- Forskningsrapport nr 6 (in Swedish). Statens institut för byggnadsforskning, Gävle, Sweden.

Tolstoy, N., Svennerstedt, B., 1984. Reparationsbehov i bostäder och lokaler Statens institut för byggnadsforskning, Meddelande M84:10 (in Swedish). Gävle, Sweden .

Ürge-Vorsatz, D., Novikova, A., Köppel, S., Boza-Kiss, B., 2009. Bottom–up assessment of potentials and costs of CO_2 emission mitigation in the buildings sector: insights into the missing elements. Energy Efficiency, 2 (4), 293-316.

Verbeeck, G., Hens, H., 2005. Energy savings in retrofitted dwellings: economically viable?. Energy and Buildings, 37 (7), 747-754.