Retrofitting Measures for Energy Savings in the Swedish Residential Building Stock—Assessing Methodology

Érika Mata **Angela Sasic Kalagasidis** **Filip Johnsson**

ABSTRACT

The aim of this work is to develop a bottom-up methodology that can assess energy efficiency and carbon dioxide (CO_2) mitigation strategies in the existing building stock. The work concerns the European building stock and is part of an overall analysis of how the European energy system can be transformed to be more sustainable. This paper reports on the validation of the methodology through its application to a sample of 1400 buildings representative of the Swedish residential stock based on data from 2005. Energy and CO_2 assessments are performed; all the resultant potentials are presented as a function of costs for the energy-saving measures studied. The results obtained for Sweden are compared to results available in the literature and discussed in relation to the further application of the methodology to the European building stock as a whole. Such application must take into account national differences in energy supply systems (heat and electricity) and characteristics of the building stock. In addition, the use of sample buildings is data intensive, and data may not be available for some European Union member states. Thus, the next step should be to further develop the model so as to be able to also use archetype buildings instead of sample buildings, allowing the use of national statistics and general information on building characteristics as model input. Transaction costs and interactions of demand side and supply side should also be included in the cost calculations.

INTRODUCTION

The worldwide residential sector consumes 16%–50% of total energy use, while the corresponding figure in Europe is 40%, although it is lower in Northern Europe (e.g., 31% in the United Kingdom, 21% in Norway, and 19% in Sweden) (Saidur et al. 2007). In developed countries, turnover in building stock is low and the greatest challenge to successful reduction of energy consumption in the building sector is to find effective strategies for retrofitting existing buildings. Yet, significant improvements are possible by applying available technologies and measures, of which many have been declared cost-effective (Levine et al. 2007; Clinch et al. 2001; IPCC 2007). To develop energy efficiency strategies for building stocks, there is a need for simplified methodologies and tools to assess the best steps to take according to the characteristics of the stock analyzed. Swan and Ugursal (2009) reviewed available models for assessing the effect of energy efficiency measures in the residential sector and concluded that so-called bottom-up modeling of buildings is required to determine the impact of new technologies. Such modeling is based on calculation of the energy consumption of an individual building or groups of houses with the results then extrapolated to represent an entire region. Methodologies for the assessment of potentials and costs of carbon dioxide (CO_2) mitigation in buildings given in the literature (SDC 2006; Levine et al. 2007; McKinsey 2008, 2009) are based on data from bottom-up studies. As Levine et al. (2007) conclude, it is essential that such bottom-up studies estimate potentials for energy efficiency as a function of cost categories so that these can be compared with certain criteria (e.g., discount rate, baseline year, and target year).

The literature gives a number of bottom-up methodologies to assess potential reductions of energy consumption and/or CO_2 emissions in buildings (Farahbakhsh et al. 1998; Balaras et al. 2000; IDAE 2003; Larsen and Nesbakken 2004; Ramirez et al. 2005; Griffith and Crawley 2006; Nemry et al.

***Érika Mata** is a PhD student and **Filip Johnsson** is a professor in the Department of Energy and Environment and **Angela Sasic Kalagasidis** is an assistant professor in the Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden.*

2008; Swan et al. 2008). These methodologies apply models designed to obtain a comprehensive thermal performance of one building at any stage of its design process (EPIQR 1996; DOE 2008; NRC 2008; DOE 2009; ESRU 2010). This type of modeling is based on a detailed description of the building with extensive input requirements and typically shows high computational times (partly since they also often feature detailed graphical illustrations of the results). Swan and Ugursal (2009) give high requirements of detailed data and computational intensity as the main negative attributes of bottom-up engineering models.

There are only a few examples of work available that developed methodologies assessing energy efficiency and CO_2 mitigation strategies for an entire building stock. Clinch et al. (2001) and Balaras et al. (2007) provide results, but their methodologies are not described in detail. Hinnells et al. (2007) and Shorrock et al. (2005) explain their specific simplified models, which they applied to the UK building stock; Hinnells et al. used the UKDCM2 model and Shorrock et al. the BREDEM-12 model. These authors developed a methodology where the calculated amount of energy saved by domestic energy efficiency measures is converted to carbon emission savings, using carbon intensity factors for fuels. They calculate the cost saving for each measure, and they express the results as cost-effectiveness on a net annual cost basis. SGSR (2009) have recently developed a carbon assessment model called DEMScot, which was developed to allow the Scottish government to investigate the impact of different policy measures aimed at reducing CO_2 emissions in the housing sector. Although the three above works give valuable information on how to evaluate energy efficiency measures for a building stock, the models and methodologies are tailored specifically to the region for which they were developed (UK and Scotland) and therefore cannot be used in this study. Finally, BFR (1996) calculated the investment costs and opportunities for energy efficiency in the Swedish building stock, using the model MSA (BFR 1984, 1987) for residential buildings and the model ERÅD (Göransson et al. 1992) for commercial buildings. They also discuss how the techno-economic potential could be achieved up to year 2020, including the new buildings to be built. The techno-economic potential of the measures is calculated according to the cost savings.[1] These savings were used as basis for the first Swedish energy saving plan and have since been used in all the national energy efficiency assessments. However, these two models (MSA and ERÅD) are not readily available. In summary, there are bottom-up methodologies that use complex models developed for other purposes than the one in focus in this work, and the few methodologies reported that are in line with the aim of this work either were developed for a specific region or are not readily available.

1. Cost savings are defined as the sum of the investment and the present value of the annual maintenance cost of the efficient alternative, divided by the present value of the cost of the annual energy savings (Government Bill 1977/78:76) (Prop 1977).

Therefore, the aim of this study is to develop a bottom-up methodology that can assess energy efficiency and CO_2 mitigation strategies for building stocks. The work is part of a project on how the European energy system can be transformed to be more sustainable, with special focus on meeting targets on energy efficiency, reductions in CO_2 emissions, and increased use of renewable energy (AGS 2009). This paper reports the modeling details and the model validation on a sample of 1400 buildings that are considered representative of the Swedish residential building stock. This first step in the methodology development was performed within the framework of the so-called BETSI program (BETSI 2009), initiated by Boverket (the Swedish National Board of Housing, Building and Planning). The energy efficiency measures considered are presented as potentials and costs for increased energy efficiency and reduction in CO_2 emissions. The costs are calculated for each measure and building assuming certain discount rates, pay-back times, and future energy prices.

METHODOLOGY

The methodology was developed to meet the following objectives:

1. To be simple both with respect to the description of the buildings and the model complexity in order to reduce computational time and amount of input data.
2. To allow modeling a building stock of an entire region or country on a level that allows aggregation to Europe as a whole.
3. To allow assessment of the effects of different energy efficiency measures.
4. To allow assessment of the costs per energy and CO_2 saved, meeting certain criteria (e.g., discount rate, baseline year, target year).
5. To allow easy and quick change of inputs and assumptions in the model.

To accomplish these objectives, the complexity of the model has to be limited in order to use inputs from available databases and to facilitate low calculation time. Reducing input data will make it more likely that efforts will be made to gather data in regions where these data are lacking. Therefore, the buildings are described in the model through a restricted number of parameters, and the outputs from the model are given in an aggregated form for the building stock considered. The model is a bottom-up engineering model, i.e., the calculation of energy consumption of a sample of individual buildings is based on the buildings' physical properties and energy use, and the results are scaled up to represent the region. The sample of buildings is taken as representative for the region to be evaluated. The energy use is calculated for the existing stock in a reference year (2005 for this case study) and then compared with corresponding calculations for which various energy efficiency measures are applied, taking into account the estimates of costs and carbon intensities of fuels and the estimated capital costs for the efficiency measures. Only existing buildings are studied, and growth in the stock is not considered (i.e., renovation and demolition rates are not considered).

The bottom-up simulation model was developed in Matlab and Simulink (MathWorks 2010). The simulation model consists of two parts—a Simulink model that solves the energy balance for buildings and a code written in Matlab that handles input and output data from the Simulink model. The accuracy of the energy balance model (in Simulink) was tested and validated for two buildings: one office building located in Barcelona, Spain, which is described in detail by Mata and Claret (2008), and one residential building in Köping, Sweden, which is described in detail by Sasic Kalagasidis et al. (2006). Further details on the validation are given by Mata et al. (2009). For the Spanish office building, where the cooling demand is covered by natural ventilation only, the indoor temperature during a warm week was calculated and compared to the measured indoor temperatures. The results were reasonable but not in full agreement with the measurements due to uncertainties in some of the input values, given the characteristics of the building (i.e., large glass façades, a ventilated basement, natural ventilation, and high exposure to the sun), but also due to the simplified modeling approach. A more detailed simulation of the building with Design Builder (DB 2010), which allows a more detailed simulation of the natural ventilation, gave better results. Yet, the modeled heating demand with the present simulation model, 76.6 kWh/m^2·yr, is within the range of measured heat consumption for similar buildings in the same campus (49.6–85.4 kWh/m^2·yr). As for the residential building, the calculated heat demand was comparable to measured data: measured consumption in 2002 was 97.4 kWh/m^2·yr, and the calculated demand for the same year is 98.2 kWh/m^2·yr.

Baseline Energy Use: Large-Scale Validation of the Model

The simulation of the energy consumption for the sample of reference buildings and for the baseline year serves as a large-scale validation of the model. As indicated previously, the building stock is represented by 1400 buildings, chosen in cooperation with Statistics Sweden (SCB 2008), as statistically representative of the Swedish housing stock (the commercial building sector is not included). Data on the buildings were collected by Boverket through field investigation (the BETSI program), which focused on the current status of the building stock in terms of energy use, technology status, indoor air quality, damages, and maintenance. Approximately 1800 energy audits were carried out by 50 inspectors who had training on the survey methodology used. 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 radon and volatile organic compound concentrations). In addition, tenants filled out a questionnaire on their age, their health status, perceived indoor air quality in the dwellings, domestic appliances used, tenure status, etc. (about 50% responded; see Boverket [2009] for further details).

Based on the information collected, Boverket provided a set of input parameters for the energy calculations. The parameters are summarized in Table 1 and include building geometry and properties of the construction materials as well as energy characteristics of the subsystems and the required indoor temperature.

The building stock is divided into two type categories—single family dwellings (SFDs) and multi-family dwellings (MFDs)—and into five groups according to the year the buildings were built (before 1960, 1961–1975, 1976–1985, 1986–1995, and 1996–2005; the divisions are according to changes in building codes and building techniques). The buildings were chosen from 30 different municipalities according to their population and geographic location in order to have a good distribution of municipalities of different sizes and different climate regions. In all, this corresponds to 300 cate-

Table 1. Model Parameters Used to Characterize the Energy Use in the 1400 Buildings Modeled

Description	Unit
Area of heated floor space	m^2
Total external surfaces	m^2
Total window surface area	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-factor 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	$W/(L/s)/m^2$
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
Minimum ventilation flow rate (sanitary ventilation)	$(L/s)/m^2$
Natural ventilation flow rate	$(L/s)/m^2$
Average constant gain due to people in the building	W/m^2
Average power demand for hot water production	W/m^2

gories with respect to combinations of type, age, and location. Meteorological data is generated by Meteonorm (Meteotest 2009) as an average for the period 1996–2005. The hourly values required for the year are outdoor temperature (°C), global and diffuse radiation on horizontal surfaces (W/m^2), and normal direct radiation (W/m^2). Effects of possible anthropogenic climate change were not considered.

The building is modeled as one thermal zone (ISO 2004). The thermal inertia of the building is represented by its effective internal heat capacity, C, according to ISO 13790 (ISO 2004), which is determined by summing the volumetric heat capacities of the building elements in direct contact with the internal air, such as internal layers of exterior walls, internal walls, and middle floors. It is assumed that the indoor air temperature and the temperatures of all internal layers are the same. Therefore, the change of indoor air temperature and the heat needed for heating and cooling of the buildings are found from the differential energy balance equation:

$$C \cdot \frac{dT_{int}(t)}{dt} = q_t(t) + q_v(t) + q_r(t) + q_{int}(t) + q(t) \quad (1)$$

where

C = effective internal heat capacity of the building, J/K
T_{int} = indoor air temperature, °C
q_t = transmission heat losses through the building envelope, W
q_v = ventilation heat losses, including sanitary and natural, W
q_r = solar radiation gains through windows, represented by one horizontal window, W
q_{int} = total internal heat loads, including lighting, appliances, occupancy, and heat released to the indoor air by other building systems, e.g., fans, W
q = heat power needed (for heating or cooling) to maintain the indoor air temperature at desired levels, W

The equation is numerically solved in the Simulink model by using the explicit time scheme. Transmission heat losses are calculated for the average thermal transmittance of the total surface of the building envelope.

Ventilation is composed of sanitary and comfort ventilation. The sanitary ventilation stands for the minimum ventilation flow rate required to ensure a healthy indoor environment in buildings, while the comfort ventilation represents the ventilation through windows when the indoor air temperature exceeds some upper comfort limit. The sanitary ventilation is provided either naturally (in most of the SFDs built before 1975 and in half of the MFDs built before 1960) or mechanically, using different ventilation systems. According to the results of the measurements within the BETSI program, the sanitary ventilation is estimated to a value of 0.23 L/s/m^2 if provided naturally and to a value of 0.35 L/s/m^2 if provided mechanically, and it is used as a constant flow rate in the simulations. The comfort ventilation flow rate is also estimated from the measurements to a constant value of 0.7 L/s/m^2. Because of the specific requirements from Boverket, the influence of wind on natural ventilation was not taken into account in this study. However, if necessary, the model can be upgraded for the calculation of variable ventilation flow rate (governed by wind or stack effect) through openings and leakages in the building envelope.

In buildings without heat recovery from exhaust air, the temperature of the supply air equals the outdoor air temperature. If a heat recovery system is present, the temperature of the supply air is found from the following:

$$T_{vent}(t) = T_{out}(t) + H_{Rec\_Eff} \cdot [T_{int}(t) - T_{out}(t)] \quad (2)$$

where

T_{vent} = temperature of supply air, °C
T_{out} = outdoor air temperature, °C
H_{Rec_Eff} = efficiency of the heat recovery unit (0–1); set as 0 when the outdoor air temperature exceeds 15 °C and therefore $T_{vent}(t) = T_{out}(t)$

In the model, the intensity of solar heat gains through windows can be calculated for different window orientations and tilts. However, a simplified approach is tested and verified for the Swedish climate conditions (characterized by moderate solar radiation intensity). In this approach, one horizontal window replaces the total area of all windows in the building. The difference in solar irradiation on differently oriented façades is compensated by a constant, which is approximated to 0.65 (Mata and Sasic Kalagasidis 2009). Internal heat loads include heat generated in the building by internal sources other than the space heating system, i.e., metabolic gains from occupants and the heat released by the appliances, lighting devices, and ventilation fans.

Heat demand is defined as the heating power required to maintain the indoor air temperature at a given level. An ON-OFF control system is used in the model; that is, the heating system is turned ON if the indoor air temperature is lower than a minimum indoor temperature, Tr_{min}. Otherwise, the heating is OFF. The value for Tr_{min} used in this study is 21.2°C, according to the results of the measurements within the BETSI program given in Boverket (2009). The heating system is characterized by a finite power and response time. Cooling demand is calculated in a similar way. In buildings with mechanical supply-exhaust ventilation systems or exhaust air heat pumps, the part of the heating demand for the sanitary ventilation losses recovered in a heat exchanger is also taken into account. Therefore, the total energy demand in the building is given by the following:

$$E_{Tot} = D_{El} + D_{Heat} + D_{Cool} + D_{HotW} - Q_{HR} \quad (3)$$

where

D_{El} = annual electricity demand, including the electricity required for lighting, appliances, hydronic pumps, and fans, kWh/yr

D_{Heat} = annual heating demand, kWh/yr
D_{Cool} = annual demand for cooling, kWh/yr
D_{HotW} = annual heat demand for hot water, kWh/yr
Q_{HR} = annual heat recovered, kWh/yr

Additional details on the modeling and its implementation are given by Mata and Sasic Kalagasidis (2009).

The energy use in the entire residential building stock is obtained by weighting (up-scaling) of the calculated heating, hot water, and electricity demands in the sample buildings. The weighting coefficients are estimated from the statistical data about the building characteristics and their number in the country. As an example, if the stock of the country consists of 20,000 apartment buildings of a certain age and in a certain climate region, and 25 of them were selected to be investigated, the weighting coefficient is 20,000/25 = 800. It should be noted that the climate data used in the simulations represent typical design years for the period 1995–2005 (Meteotest 2009), while the energy data in the official statistics date from the year 2005. However, the difference between the heating degree-days in the data from Meteonorm and the actual climate in the year 2005 is shown to be only 2%, so the calculated energy demand is considered representative for 2005. This result is called *baseline energy use*. For the final comparison with the data in the official statistics, Boverket has recalculated the baseline energy use into the energy delivered, by taking into account the types and efficiencies of the heating and electricity systems in the housing stock (i.e., percentages of oil, gas, pellets, wood, electricity, and district heating in heating and hot water demand). This final comparison showed a difference of 5% between the calculated energy (delivered) and the number in the statistics; thus, the baseline energy use is considered validated.

Energy-Saving Measures Considered

A total of 12 types of measures, outlined in Table 2, were assessed. Measures 1 to 6 and measure 11 are technical—that is, they only require replacement of a part of the building or its systems by a more energy-efficient component/system. The remaining measures involve behavioral changes and therefore are applied by changing the assumptions of certain input parameters. For instance, a reduction of the use of hot water is considered to correspond to substitution of the existing taps with aerator taps but also requires adequate operation by the occupants. In order to reduce the indoor temperature to 20°C, it is necessary not only to install thermostats but also for the occupants to set an adequate indoor temperature. Finally, for lighting and appliances, it is assumed that the combined changes in the efficiency, number of units, and user operation will result in a reduction by 50% of the power required (the reduction is calculated with respect to the baseline year, 2005).

The potential savings have been calculated in two different ways, according to what was suggested by Boverket. First, measures were applied one by one according to the type of measure (i.e., only one at a time) to get information of the potential energy saving from each measure. Yet, these potentials cannot be added to obtain the overall effect from the measures (although this methodology is seen in the literature, e.g., Farahbakhsh et al. [1998], Balaras et al. [2000], Clinch et al. [2001], IDAE [2003], Larsen and Nesbakken [2004], Ramirez et al. [2005], Griffith and Crawley [2006], Balaras et al. [2007], Nemry et al. [2008], and Swan et al. [2008]). Such an approach will obviously result in a risk of overestimating the overall energy savings. Here, this approach only serves the purpose of a first assessment of the cost-effectiveness of each of the 12 measures investigated. As for the main analysis, the measures were applied aggregated, since the effects of one measure might influence another. For the aggregation, the measures were applied according to their annual costs, in increasing cost order. Other groupings of the measures for technical or operational reasons were not considered and are left for future work. For instance, it may seem reasonable to replace a window and at the same time as the envelope is checked for air leakages. To exemplify how it is done in this work: if the price for replacing a window is 5 cent€/yr per kWh/yr saved, and the price for sealing air leakages is 10 cent€/yr per kWh/yr saved, first the windows are replaced and then all the measures cheaper than 10 cent€/yr per kWh/yr saved are applied before sealing the envelope.

Costs of Reducing Energy Use and CO_2 Emissions

This work evaluates two costs related to implementation of the previously mentioned energy efficiency measures: the cost for reducing energy use and the cost for reducing CO_2

Table 2. Energy-Saving Measures Assessed in the Present Work

Measure	Description
1	Change of U-factor of cellar/basement
2	Change of U-factor of façades (different types)
3	Change of U-factor 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	50% reduction of power for lighting
8	50% reduction of power for appliances
9	Reduction of power used for the production of hot water to 0.80 W/m^2, for SFDs
10	Reduction of power used for the production of hot water to 1.10 W/m^2, for MFDs
11	Change of electrical power to hydro pumps
12	Use of thermostats to reduce by 1.2°C indoor air temperature to 20°C

emissions. These are here defined as the incremental cost of implementing the energy efficiency measures compared to the baseline case, and costs are either expressed as euro per energy (kWh) saved or euro per ton of CO_2 emissions avoided on a yearly basis. As has been indicated, the baseline is taken as the Swedish residential building stock as it was in 2005. The cost represents the pure "project cost" (i.e., investment) to apply (i.e., install and operate) the energy efficiency measures. Capital availability is not considered a constraint. Thus, energy saving cost is written as the following:

$$Cost_E = \frac{NAC_{EA} - NAC_0}{ES} \tag{4}$$

where

NAC_{EA} = net annual cost of the efficient alternative, €/yr

NAC_0 = net annual cost of the reference case (year 2005)

ES = energy saved due to the application of the measure, kWh/yr

The CO_2 avoidance cost is written as the following:

$$Cost_{CO_2} = \frac{NAC_{EA} - NAC_0}{Em_0 - Em_{EA}} \tag{5}$$

where

Em_0 = CO_2 emissions for the reference case (year 2005), tCO_2e/yr

Em_{EA} = CO_2 emissions for the efficient alternative, tCO_2e/yr

The corresponding annual energy saving costs are

$$NAC = EAC - S \quad \text{(Shorrock et al. 2005)} \tag{6}$$

and

$$EAC = \frac{c \cdot r}{1-(1+r)^{-n}} + M \tag{7}$$

where

EAC = net annual energy saving cost (i.e., the annual cost of the investment required to apply the measure over its entire life), €/year

S = annual cost of the energy saved, €/yr

C = cost of the measure, €

r = discount rate (0–1)

n = lifetime of the measure over witch the annual cost saving is supplied, yr

m = extra maintenance cost of the efficient alternative, €/yr

The costs used consist of the costs of material and labor for work related to implementation of the energy efficiency measure, including taxes (i.e., consumer prices, excluding VAT). This means that most of the energy-saving measures are assumed to be applied at the same time as ordinary maintenance or retrofitting actions, and therefore only the extra costs for the energy savings are taken into account. Thus, if, for example, the façade is to be renovated, the insulating material is taken into account but not the scaffolding, as recommended in Hermelink (2009). Costs for planning, information retrieval, and other client costs are not included (i.e., "transaction costs" are excluded), although costs for moisture safety planning and costs for conservation issues and aesthetic issues can increase the cost of an energy-saving measure. The net annual costs used, defined in Equation 7, are based on data from Boverket (2009). The annual maintenance costs, when such are present, are assumed to be the same each year. The discount rate is 0.04 (i.e., 4%).

Carbon intensities ($kgCO_2e/kWh$) for the energy sources were assumed constant over the years.

The consumer energy prices (exclusive of VAT but including all other taxes) for the period from 2005 to 2007 are based on data from Göransson and Pettersson (2008), who updated values presented by Dalenbäck et al. (2005) for the period from 1993 to 2004, so as to be valid for the period from 2003 to 2007, taking into account the mix of energy sources for each type of building. Pettersson and Göransson reported, on average, an increase of the prices of about 15% for SFDs and about 10% for multi-residential buildings and locals. The estimated consumer energy prices for the period from 2008 to 2020 are based on data from BFR (1996). Those data are further developed by Profu (2008), including prices for electricity, district heating, oil, natural gas, and biomass.

RESULTS AND DISCUSSION

Potential Energy Savings for Swedish Housing

The simulations give a baseline energy demand for the Swedish residential building stock in the year 2005 of 92.3 TWh/yr. This result corresponds to the value given by the national statistics, as discussed by Boverket (2005, 2009), using the already mentioned average ventilation rates measured within the BETSI program (Boverket 2009). However, the indicated values for SFDs are lower than the 0.35 $L/s/m^2$ recommended by the Ministry of Health as a value for ensuring adequate indoor air quality. If the ventilation rate is increased to 0.35 $L/s/m^2$ in all SFDs, according to the calculations in this work the demand increases to 97.7 TWh/yr. Since adequate indoor air quality is to be achieved in the future, the energy demand with increased ventilation was used as a baseline value to calculate the potential energy savings.

Table 3 shows the technical potential energy savings obtained for the 12 measures listed in Table 2. As indicated previously, the savings are given both as a result from applying them on an individual basis ("Individual") and when applying them aggregated ("Aggregated"). As can be seen, the different measures give savings between 0.6 and 13.6 TWh/yr. The measures that give the highest savings are those involving heat recovery systems and a reduction of indoor temperature. The upgrading of the U-factors of cellars/basements and of façades (different types) and the replacement of windows provide a

Table 3. Results of Energy Saving Potentials (TWh/yr) from This Work

Measure	Individual	Aggregated
Total	66.6	56.3
Change of U-factor of cellars/basements	7.4	6.2
Change of U-factor of façades (different types)	7.3	6.2
Change of U-factor of attics/roofs (different types)	3.5	3.0
Replacement of windows (U-factor)	6.5	5.5
Ventilation with heat recovery, SFD	11.9	10.1
Ventilation with heat recovery, MFD	9.6	8.1
50% reduction of power for lighting	0.3	0.3
50% reduction of power for appliances	0.9	0.8
Reduction of power used for the production of hot water to 0.80 W/m^2, for SFD	2.6	2.2
Reduction of power used for the production of hot water to 1.10 W/m^2, for MFD	2.1	1.8
Change of electrical power to hydro pumps	0.6	0.5
Use of thermostats to reduce indoor air temperature to 20ºC	13.6	11.5

saving of about 7 TWh/yr each. According to the model, the maximum energy savings that could be achieved by applying the measures aggregated according to their cost-efficiency would be 56.3 TWh/yr. This total technical potential is higher than the 33.7 TWh/yr reported by Sandberg (2007), but Sandberg used a top-down model and applied different measures from those of this work (e.g., not including reduced indoor temperature). More work is required in order to understand the difference from the present work.

BFR (1996) reports a techno-economic potential savings (i.e., considering only the savings that are profitable) of 30–45 TWh/yr, depending on the assumptions made. In this work, it is found that 30.5 TWh/yr could be saved by applying profitable measures. Dalenbäck et al. (2005) updated the energy prices and assumptions from BFR and reported a total potential techno-economic savings of 26.0 TWh/yr, while Göransson and Pettersson (2008), updating again energy prices and assumptions, reported a total potential techno-economic savings of 41.0 TWh/yr. These three studies all applied the previously mentioned cost savings and used an interest rate different from this work (6% instead of 4%). Also, their studies are based on the description of the Swedish buildings as they were in the year 1995 (Boverket 1995), while this work is based on the Swedish buildings as they were in the year 2005. More work is required in order to understand the difference from the present work.

Results of Costs per Energy and CO_2 Emissions Saved

The investment required to implement all the measures assessed in this work and achieve the aggregated technical potential savings of 56.3 TWh is 5.7 Billion[2] €. The chart relating the potential savings and the investments is shown in the national report (Boverket 2009). In the previous national report (BFR 1996), it is stated that 25 Billion € are required to achieve a total potential savings of 32.5 TWh. A reason for this big difference from the present work could be that in the present study some investment costs have been input as zero in cases where the measure is assumed to take place in any case (for other reasons), such as for changes in lighting and some appliances. In addition, there have obviously been developments in technologies (and costs) since 1996.

Figure 1 shows the data from the simulations given in Table 3 plotted as incremental costs and corresponding reductions in energy use. The average cost for the energy efficiency measures investigated is 2.4 cent€/kWh/yr, covering a range from –7.6 to 23.3 cent€/kWh/yr. The profitable measures (negative costs in Figure 1) are those that depend both on technical improvements (e.g., more efficient lights and appliances or installation of thermostats, aerator taps, or dual-flow WCs) and on behavioral changes (i.e., lifestyle changes). As indicated previously, for lighting and appliances the equivalent annual cost (as defined in Equation 7) of a reduction in electricity consumption is assumed to be zero, since there will not be any other possibility in the future than to buy more efficient appliances and lighting. This is assumed because in Sweden there are nearly only energy certified appliances available, and shortly in all the European Union incandescent light bulbs will no longer be available. Such efficient lighting and appliances might be more expensive than their less efficient counterparts. However, Mahlia et al. (2005) analyzed in detail electricity savings from improvements in lighting and concluded that electricity savings over time are significant enough to not only pay for the new lighting but also produce return on investment. However, occupant behavior and penetration rates were not assessed.

Simulations give heat recovery as a low-cost measure to apply (0.5 cent€/kWh), especially for SFDs, where normally there is not a heat recovery system. As for the retrofitting of the envelope, simulations show that replacement of windows is much less expensive than retrofitting the façade, as can be seen from Figure 1, while the potential savings to be achieved by each measure are similar, as can be seen in Table 3. For the measures that would reduce the energy demand for heating, in the case of an apartment building where apartments are rented out (as opposed to cooperate ownership by tenants, which is also a common form of ownership in Sweden), the owner

2. Billion in short scale, i.e., 10^9. Exchange used is 1 € = 10 SEK.

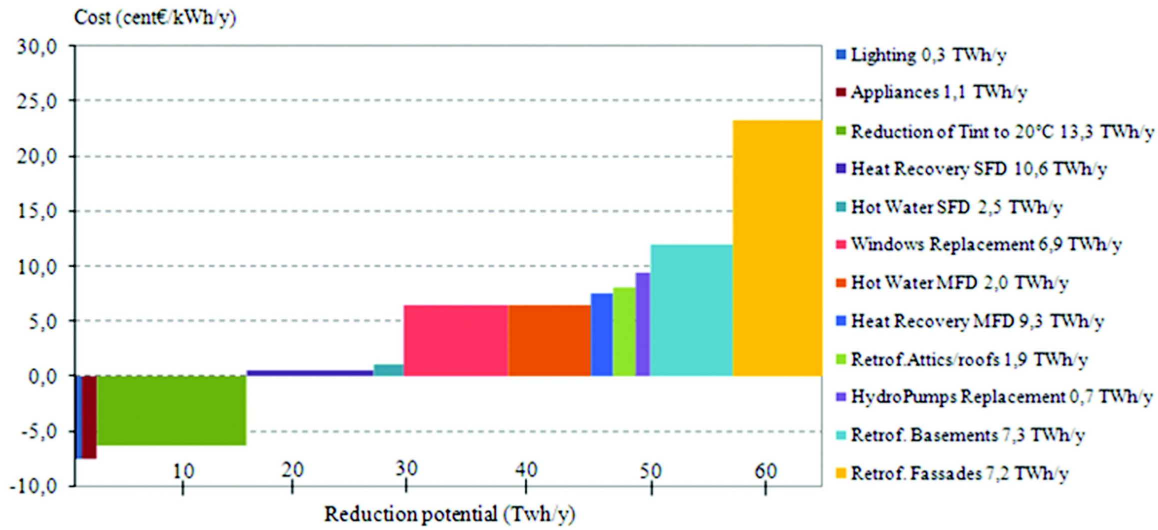

Figure 1 *Average costs per type of energy efficiency measure as obtained from simulations in this work.*

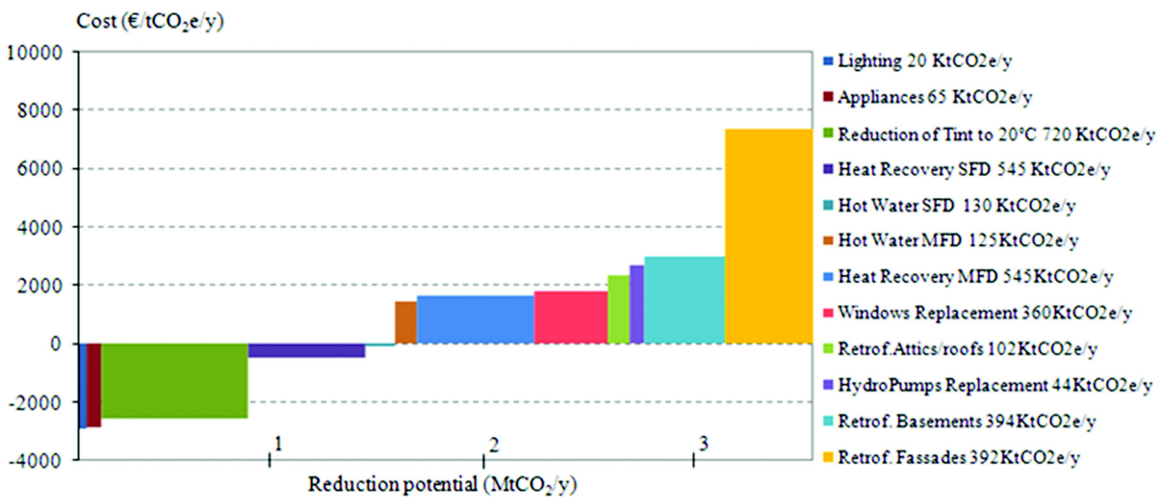

Figure 2 *Potential for CO_2 reduction and the associated average costs per type of measure as obtained in this work.*

would pay for the improvement but would also save the money on the heating bill if the heat is provided by district heating (since in Sweden heating is normally included in the rent). The rent might as well be increased for the owner to cover investments.

For locations with milder climates than Sweden, the potential energy savings due to the improvement of ventilation systems with heat recovery is expected to be lower. The ranking of resulting cost-effectiveness for Swedish housing shown in Figure 1 does not agree with what is reported for the European residential buildings sector. The European commission (CEC 2006) identified retrofitting of façades and roof insulation as the most cost-efficient measures for European residential buildings, while the results reported in this paper for Sweden (Figure 1) show that retrofitting of façades is the most expensive measure to apply. The reason for this difference is not yet known.

The total potential for CO_2 reduction as obtained from the modeling is 3.6 $MtCO_2e$/yr, as can be seen in Figure 2. This is 60% of the emissions from the Swedish building sector. The average abatement cost is 311 €/tCO_2e (ranging from –2932 to 7344 €/tCO_2e). The high costs are due to the characteristics of the Swedish energy supply, which is already almost without CO_2 emissions. This results in very high costs for some of the measures investigated, up to as much as 48,000 €/tCO_2e (if examining measures on a more refined level than is resolved in Figure 2). However, 52% of the measures assessed are profitable (the negative cost in Figure 2).

McKinsey (2008) assessed greenhouse gas abatement opportunities in all sectors in Sweden up to the year 2020. As for the retrofitting of existing homes, they report a cost of 640 €/tCO_2e for "Multi-family homes retrofit 80kWh/m^2," which can be compared to the average from this work, which is 311 €/tCO_2e. However, the McKinsey report does not provide the methodology used and the specific measures included, which makes it difficult to draw any detailed conclusion from the comparison.

Discussion

The methodology of this work relates energy efficiency measures to a baseline energy use (also called *useful energy*) in the year 2005, while the statistics only report final energy (also called *delivered energy*). The difference between such data and the energy use of this work recalculated as delivered energy was 5%. The accuracy of the baseline should not be decisive, since the aim is to estimate the potential energy savings, but rather the resulting potentials compared to such a baseline.

For the measure in which the building envelope is retrofitted, the lifetime of the systems was set to 40 years and equal to the depreciation time. Obviously, this is a strong simplification since a house owner will most likely have a higher requirement on return (payback time) of the investments. For the case of the use of thermostats to reduce the indoor temperature to 20°C, the lifetime considered is 15 years, that is, the life of the thermostat. Of course, achievement of the reduction of indoor temperature also requires adequate operation by the occupants. Such constraints may be called "transaction costs" but have not been assessed in the present work; neither have been addressed the interactions between demand side and supply side (e.g., a demand reduction would influence energy prices and thus the estimated cost of the energy saved). Cost calculations will be improved with respect to these issues in future work. In addition, further work could also include a simplified calculation of the costs, where the net annual costs will be calculated only according to the type of measure.

Modeling based on sample buildings strongly depends on the quality of input data, and even if the model is simplified and requires a minimum of input data, such data are not always available in a way that they are representative for an entire building stock of the region to be investigated. Thus, the next step should be to improve the model so that it is able to use archetypes instead of sample buildings. Archetypes should not represent one building existing in reality but should be defined according to data available in literature and statistics. Such data are available for most European countries; taking Sweden as an example, it should be possible to compare the present results with results based on archetype buildings. Obviously the results depend on the characteristics of the buildings, but they also depend on the energy/carbon intensity of the building sector studied. In this respect, the results reported in this work for Sweden differ from the available results for the European housing sector and there is a need for bottom-up studies for building stocks representative for different regions in the European Union. In addition, the building physics model has to be tailored to the characteristics of nonresidential buildings.

The simplified one-zone model for the buildings might not be sufficient for southern European regions where the climate requires more active operation of buildings to maintain a steady comfort temperature, especially if applying passive systems (e.g., natural ventilation), or for buildings with distinct thermal zones. Developing the model to include the possibility to base calculations on archetype buildings might require improvements of how the energy use is described in the model. Moreover, the simplification of the windows to one horizontal window may also have to be reviewed for regions and climates with strong solar radiation.

CONCLUSIONS

A methodology for assessment of energy efficiency and CO_2 mitigation strategies for building stocks is presented in this work. The aim has been to find a simple methodology that can address an entire building stock. The methodology is based on an engineering bottom-up model using a limited sample of buildings. Sweden was used as test case, with data from 1400 buildings considered representative of the Swedish residential building stock.

Although the methodology applied in this work is based on a simplified engineering bottom-up model, a set of input data from a sample of buildings is required on a level that makes those buildings representative for the entire building stock of the region studied. In several regions such data may not be available, and therefore it should be of interest to develop the modeling methodology to also facilitate the use of archetype buildings instead of sample buildings. As a first step, this can be done for Sweden as a test case, comparing an archetype building approach with the present work.

The application of the methodology to the case study shows that the aggregated technical potential for energy savings in the Swedish residential sector is about 56 TWh/yr, corresponding to 58% of the energy use in the baseline year. The sum of the individual technical potential reduction in energy use of each measure is 68%. The modeling shows that a reduction in indoor temperature to 20°C reduces the annual energy consumption by 13.6 TWh, while upgrading the ventilation with heat recovery systems reduces the annual consumption by 11.9 TWh for SFDs and by 9.6 TWh for MFDs. The results give that upgrading the U-factors of cellars/basements and façades and replacing windows provide a savings of about 7 TWh/yr each. Reduction of the demand for lighting and appliances and reduced indoor temperature appear as profitable measures (negative costs). Heat recovery is a low-cost measure (0.5 cent€/kWh/yr), especially for SFDs. As for the retrofitting of the envelope, the replacement of windows is a measure much less expensive than the retrofitting of the façade, while the potential energy savings from these two measures are similar.

The total potential for CO_2 reduction is 3.6 MtCO_2e/yr, which is a reduction by 60% of the emissions of the Swedish building sector. The average CO_2 abatement cost obtained is high due to the fact that the Swedish building sector already is more or less CO_2 free. The aggregated technical potential savings presented for each measure include the interactions between the different energy-saving measures studied and are thus ready to be used as a basis for further top-down analysis. However, cost calculations could be developed to include complexities (transaction costs, demand side and supply side rebounds, etc.).

ACKNOWLEDGMENTS

This work was funded by the Alliance for Global Sustainability project "Pathways to Sustainable European Energy Systems" and the Agency for Management of University and Research Grants [Agència de Gestió d´Ajudes Universitaries i de Recerca, AGAUR] programs BE 2008 and BE-DGR 2009. Björn Mattsson from Boverket and Anders Göransson from Profu are gratefully acknowledged for their contributions to fruitful discussions.

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