A modelling strategy for energy, carbon, and cost assessments of building stocks.

Title

A Modelling Strategy for Energy, Carbon, and Cost Assessments of Building Stocks

Corresponding Author
Érika Mata
Archt., Tekn. Lic., PhD candidate
Energy Technology
Department of Energy and Environment
Chalmers University of Technology
412 96 Gothenburg, SWEDEN
Desk Tel: +46-(0)31- 772 -5250
Fax: +46-(0)31- 772 -3592
E-mail: mata@chalmers.se

Other authors
Angela Sasic Kalagasidis
Filip Johnsson

Affiliation
Chalmers University of Technology

Abstract
This paper presents the Energy, Carbon and Cost Assessment for Building Stocks (ECCABS) model, which is a bottom-up model to assess energy-saving measures (ESM) and carbon dioxide (CO_2) mitigation strategies in building stocks. The model is based on a one-zone hourly heat balance that calculates the net energy demand for a number of buildings representative of the building stock and an additional code for the input and output data. The model generates results in terms of delivered energy, associated CO_2 emissions, and the costs of implementing different ESM. The results are extended to the entire building stock by means of weighting factors. Empirical and comparative validations of the heat-balance modelling of single buildings are presented. The building stock modelling is validated against the current Swedish residential stock, for which the results of the modelling are in agreement with the statistical data. Using the model to assess a number of ESM reveals that the energy usage of the Swedish residential sector can be reduced by 55% and the associated CO_2 emissions can be reduced by 63%, with most of the ESM being cost-effective. The applicability of the model to countries other than Sweden is under investigation.

Keywords [max 10]
Energy efficiency, CO_2 emissions, building stock, assessment, costs, energy saving measures, bottom-up model

1 INTRODUCTION

The EU-27 building sector accounts for about 25% of the total final energy use (in 2008). Since the turnover of building stock is low in developed countries, the greatest challenge to reducing energy use in the building sector is to find effective strategies for retrofitting existing buildings. Significant improvements can be achieved by applying available technologies and measures, many of which are cost-effective. Modelling energy use in buildings is an important step towards designing and implementing policy measures related to energy savings in buildings. Swan and Ugursal [1] reviewed available models for assessing the effects of energy-saving measures (ESM, also referred to as *energy efficiency measures*, represent actions aimed at reducing energy demand in buildings) in the residential sector, and concluded that so-called bottom-up modelling of buildings is required to determine the impacts of new technologies. A bottom-up model of the building stock typically comprises building physics modelling for calculating the energy usage of individual buildings, and extrapolation of the results to a region or a country. Kavgic et al. [2] reviewed selected bottom-up building stock models for energy use in the residential sector and proposed that they should: (a) estimate the baseline energy demand of the existing building stock; (b) explore the technical and economic effects of different carbon dioxide (CO_2) emission reduction strategies over time, including the impacts of new technologies; and (c) identify the effects of the strategies on the quality of the indoor environment.

The available bottom-up studies and modelling methodologies to assess energy use (and/or associated CO_2 emissions) in building stocks have been reviewed recently [2–4]. Table 1 compares studies that have used an approach similar to that employed in the present work, i.e., it lists models that address an entire building stock, including building heat-balance calculations. The left-most columns in Table 1 list the modelling methodology used in the studies with respect to the temporal and spatial resolutions of the heat-balance modelling, input data handling, and types of results obtained. For studies in which already established models have been used for the heat-balance or building stock modelling, the names of the models are listed. The right-most column in Table 1 refers to specific applications of the models presented in each study, in terms of the size and location of the building stock assessed, and the subsectors included (i.e., residential and/or non-residential).

The choice of spatial and temporal resolution of the heat-balance calculations is linked to input data and calculation time requirements. The models listed have solved this differently. References [5-7] apply models that focus on detailed design of individual buildings, and which provide multi-zone analysis and hourly calculations of indoor temperatures and energy use, as well as detailed specifications of user profiles in terms of hours of occupancy, and use of building service systems and household appliances. Such detailed modelling involves time-consuming collection of the input data, as well as correspondingly detailed results, which might not be required when the focus is on analysing an entire building stock rather than an individual building. When working with a larger number of buildings, a more commonly used approach is to limit the level of detail. Thus, in the studies listed in Table 1, simplifications were achieved by limiting the temporal resolution (monthly or annually averaged energy calculations, as used in [3, 8-20]) or using pre-defined indoor air temperatures and a one-zone representation of the entire building (as in [9-20]; [8] uses three-zone modelling of the building). The data required for models that use the above-mentioned approach can be found in national statistics databases. However, the broadness of the time resolution, i.e., monthly or annual, does not allow considerations of the temporal changes in demand that result from occupancy, the use of different appliances, and the effect of solar radiation gains. Therefore, these models do not reflect the complexity of implementing measures that involve building service management or user behaviour. In addition, they do not allow analysis of the effects on indoor temperature of applying ESM. The energy model of a building stock presented in the present work combines some of the favourable features of the detailed and broader models, namely hourly calculations and the one-zone approach.

As pointed out previously [2], the availability of data may determine the structure of the model by limiting the application of the model to certain subsectors of the building sector for which data are available, i.e., residential or non-residential and subgroups thereof. Of the studies listed in Table 1, only one [5] addresses the entire building sector. Some of the listed studies have pre-defined data incorporated in the model, as is the case for the UK building stock models, which use the BREDEM model for the heat balance [3, 15, 17–20]. Thus, such country-tailored models may be adequate for addressing the country for which they have been developed, although it may be difficult to assess applicability to another country. To allow applicability to any region/set of buildings, the input data requirements in the model presented in the present paper are specified, in as much as they are generally available from different national statistics databases and surveys, so as to represent the different building types in a building stock.

Table 1. Bottom-up studies to assess energy use in (and/or CO_2 emissions from) building stocks.

Reference	Temporal and spatial resolution	Input data handling	Type of assessment	Building stock modelling system	Building heat-balance modelling	Application to geographical region(s) - Sector
5	Hourly, multi-zone	Not specified	Heating and cooling loads	Not specified	DOE-2.1E	USA
6	Hourly, multi-zone	Not specified	Energy use	DrCEUS	eQUEST/ DOE-2.2	California-NR
7	Hourly, multi-zone	Not specified	Energy use	Not specified	EnergyPlus	USA-NR
3	Monthly, one-zone	Built-in for UK homes	Energy use; CO_2 emissions	ABM implementation (using RePast) of DECarb	BREDEM	UK-R
8	Monthly, three-zone	Built-in for Canadian homes	Energy use; CO_2 emissions	CREEM	HOT 2000	CA-R
9	Monthly, one-zone	Dynamic link library	Energy use	Not specified	EPIQR	MFD in three climatic zones of GR
10	Monthly, one-zone	Not specified	Energy use; airborne emissions; costs	INVESTIMMO	EPIQR	EU-R (five selected countries)
11	Monthly, one-zone	Not specified	LCA; costs	Not specified	EPIQR	EU-25-R
12	Monthly, one-zone	Built-in for UK homes	Energy use; costs	Tobus	Based on standard EN 832	Four GR and two DK office buildings
13	Monthly, one-zone	Incorporated database	Energy and water savings; air pollutants; costs	XENIOS	Based on standard EN 833	Not specified
14	Annual, one-zone		Energy use; CO_2 emissions	VerbCO2M	Not specified	BE- R
15	Annual, one-zone	Built-in for UK homes	Energy use CO_2emissions; costs	BREHOMES	BREDEM-12	UK-R
16	Annual, one-zone	Not specified	Energy use; costs	E-SDOB	Based on heat utilisation factor (EN ISO 13790:2008)	Two regions of IT
17	Monthly, one-zone	Built-in for UK homes	Energy use; CO_2 emissions	Constructed in Microsoft Excel	BREDEM-based	UK-R
18	Monthly, one-zone	Built-in for UK homes	Energy use; CO_2 emissions	UKDCM2	BREDEM-8	UK-R
19	Monthly, one-zone	Built-in for UK homes	Energy use; CO_2 emissions	CDEM (Microsoft Excel)	BREDEM-8	UK-R
20	Monthly, one-zone	Building stock Database on linked Excel worksheets and default climate data	Energy use; CO_2 emissions; costs	DEMScot (Microsoft Excel)	Improved BREDEM-12	Scotland-R
This work	Hourly, one-zone	User defined for any building stock	Net energy; delivered energy; CO_2 emissions; costs	ECCABS	ECCABS	SE-R

R: Residential sector; NR: services sector; MFD: multi-family dwellings; BE: Belgium; DK: Denmark; GR: Greece; CA: Canada; IT: Italy; SE: Sweden; ABM: agent-based modelling; LCA: Life Cycle Assessment.

In summary, the modelling framework presented in the present paper aims to assess the effects and costs of technological and non-technological strategies for energy efficiency and CO_2 mitigation for an entire building stock (including the residential and services sectors). The model should also be capable of hour-by-hour simulations of the indoor temperature, with simplified input data (which can be expected to be generally available to describe an entire building stock) and to be easily modified and transparent. This paper first describes the model, including model validation, and subsequently provides the results of applying the model to evaluate ESM in the Swedish residential building stock.

2 SCOPE OF THE MODELLING

The model presented in the present work, which is termed *Energy, Carbon and Cost Assessment for Building Stocks* (ECCABS), is designed to assess the effects of ESM for building stocks. The main outputs from the model are: net energy demand by end-uses; delivered energy (to the building); CO_2 emissions; and costs associated with the implementation of ESM. In addition, the model aims to:

- facilitate the modelling of any building stock of any entire region or country;
- allow for easy and quick changes to inputs and assumptions in the model;
- provide detailed outputs that can be compared to statistics, as well as in a form such that they can be used as inputs to other (top-down) models; and
- be transparent.

To achieve these objectives, the complexity of the model has to be limited so as to avail of inputs from available databases and to facilitate short calculation times. Reducing the amount of input data will support efforts to gather data in regions for which information is lacking. Therefore, the buildings are described in the model with a restricted number of parameters, the outputs from the model are given in an aggregated form for the studied building stock, and the levels of input data required to describe the energy system and the possible scenarios are also limited. The model is a bottom-up engineering model, which means that calculation of the energy demand of a set of individual buildings is based on the physical properties of the buildings and their energy use (e.g., for lighting, appliances, and water heating), and the results are scaled-up to represent the building stock of the region studied. Thus, the modelling assumes that a number of buildings can be assigned as being representative of the region to be evaluated. The energy demand and associated CO_2 emissions of the existing stock are calculated for a reference (baseline) year, and the potential improvements of the ESM application are given as a comparison to the baseline. The model is written to be generally applicable and, thus, does not have any embedded data. The present paper is limited to analyses of existing buildings, which is the intended primary utility of the model.

3 MODELLING METHODOLOGY

The model was developed with the Matlab and Simulink tools [23]. The simulation model consists of two parts: 1) a Simulink model, which solves the energy balance for the buildings and provides the net energy demand; and 2) a code written in Matlab, which handles the input and output data from the Simulink model and extends the results to the building stock, while calculating delivered energy, associated CO_2 emissions, and costs of implementing certain ESM. The two parts of the model are available [24].

3.1 Net energy demand

In this paper, the energy required to satisfy specific end-uses in a building is termed the *net energy,* also commonly referred to as *useful energy*. It comprises heating, cooling, ventilation, hot water, lighting, and appliances [25]. Net energy is not what the consumer buys, but rather that from which the consumer derives benefits, after losses in the technical systems installed in the building have been taken into account (including on-site renewable energy systems). Therefore, measurement of the net energy is difficult, and it is a valuable output from the model.

The net energy demand is calculated using an energy balance model for a building. The building is modelled as a single thermal zone. The thermal inertia of the building is represented by its effective internal heat capacity, C_m, according to ISO 13790 [26]. It is assumed that the indoor air temperature and the temperature of all internal layers are the same. The modelling is carried out using a time series of climate data with a 1-hour time step and duration of 1 year. The indoor air temperature is derived from the differential heat-balance equation:

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

where C_m is the effective internal heat capacity of the building (J/K), T_{int} is the indoor air temperature (°C), q_t is the transmission-related heat losses through the building envelope (W), q_v is the ventilation heat loss (W), q_r is the solar radiation gains through windows (W), q_{int} is the total internal heat gains (W), and q is the total heat provided by the heating/cooling system (W).

Transmission heat losses are calculated for the average thermal transmittance of the total surface of the building envelope.

The ventilation flow rate encompasses sanitary ventilation and natural ventilation, i.e., heat loss due to the ventilation is modelled as:

$$q_v(t) = \frac{V_c \cdot A \cdot (\rho c_p)_a}{1000} \cdot [T_{vent}(t) - T_{int}(t)] \tag{2}$$

where V_c is the sanitary ventilation rate (l/s/m^2), ρ_a is the air density (kg/m^3), ${c_p}_a$ is the specific heat capacity of the air (J/kg K), A is the heated floor area in a building (m^2), and

T_{vent} is the temperature of the supply air (°C). The sanitary ventilation corresponds to the minimum ventilation flow rate required to assure a healthy indoor environment, and it does not necessarily have to be provided mechanically. However, not being any mechanical ventilation system in place, it might happen that the occupants do not open the windows enough to ensure a healthy indoor environment. This is what measurements prove that happens in Swedish single family houses [27]. Infiltration rates are included in the sanitary ventilation parameter because they are very difficult to measure separately. For example, a fan installed for sanitary ventilation sucks the air that comes into the building through the designed openings, but also the air that originates from infiltration. Regarding natural ventilation, it is assumed that the occupants open the windows when the indoor air temperature exceeds some upper comfort limit, T_v. Thus, natural ventilation occurs normally during the summer season. In buildings without heat recovery from the exhaust air, the temperature of the supply air equals the outdoor air temperature. If a heat recovery system is present, the supply air is preheated by the exhaust air. Depending on the outdoor air temperature T_{out}, the temperature of the supply air is obtained from:

$$T_{vent}(t) = T_{out}(t) + H_{Rec\_Eff} \cdot [T_{int}(t) - T_{out}(t)]\ , if\ T_{out} < 15℃ \qquad \text{3a}$$

$$T_{vent}(t) = T_{out}(t), if\ T_{out} \geq 15℃ \qquad \text{3b}$$

where H_{Rec_Eff} is the efficiency of the heat recovery unit (0-1).

Since the model is to be used for all buildings in a building stock, no specific orientation of the windows is considered. This simplified approach has been tested and verified for the climate in Sweden (characterised by moderate solar radiation intensity). In this approach, a single horizontal window is taken as representing the total area of all the windows in the building. The difference in solar irradiation exposure for differently oriented facades is compensated for using a constant, which is approximated as 0.65 [24]. Ongoing work by the authors with building stocks in other EU regions suggests that this constant differs according to the latitude of the geographic region studied.

Internal heat gains are designated as constant average gains and include heat generated in the building by internal sources other than the space heating system. Thus, these include gains derived from metabolic activities of the occupants, as well as the heat released by appliances, lights, and ventilation fans.

Table 2. Outputs from the model (annual values for each building analysed).

Output	Description	Unit
$\frac{D_{HotW}}{A}$	Specific net energy demand for water heating	kWh/m^2
$\frac{D_{Heat}}{A}$	Specific net energy demand for space heating	kWh/m^2
$\frac{D_{El}}{A}$	Specific net energy demand of electricity	kWh/m^2
Q_t	Transmission losses through the envelope	kWh
Q_{vSa}	Sanitary ventilation losses	kWh
Q_r	Solar radiation gains	kWh
Q_{Occ}	Occupancy gains	kWh
Q_{Lig}	Lighting electricity consumption	kWh
Q_{App}	Appliances electricity consumption	kWh
Q_{HyP}	Pumps hydro electricity consumption	kWh
Q_{Fan}	Fans electricity consumption	kWh
Q_{HeatR}	Heat recovered by supply-exhaust systems	kWh
$Q_{HeatR\ HP}$	Heat recovered by heat pumps	kWh
D_{HotW}	Net energy demand for water heating	kWh
D_{Heat}	Net energy demand for space heating	kWh
D_{El}	Net energy demand of electricity	kWh
E_{tot}	Total net energy demand	kWh
$E_{tot} \cdot W$	Weighted total net energy demand	kWh
$(E_{tot})_0$	Baseline total net energy demand	kWh
$(E_{tot} \cdot W)_0$	Weighted baseline total net energy demand	kWh
$\sum[(E_{tot} \cdot W)_0 - (E_{tot} \cdot W)_i]$	Total net energy saving	TWh

Heat demand is defined as the heating power required to maintain the indoor air temperature at a given level. A "dead-band" control system is used in the model, which means that the heating system is turned ON if the indoor air temperature is lower than a minimum indoor temperature, Tr_{min}. Otherwise, the heating is in the OFF position. The heating system is characterised by a finite power and response time. Cooling demand is calculated in a similar way, and thus does not include latent loads. 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.

The outputs from the model for each of the buildings analysed are listed in Table 2.

The computational time for practical application of the model should not be excessive. For instance, the total time for calculation for 1,400 reference buildings in 30 climate regions, as applied in the above-mentioned work with the Swedish residential stock, is 70 minutes[1].

The total net energy demand, $\mathrm{E_{Tot}}$, is calculated from:

$$E_{Tot} = D_{El} + D_{Heat} + D_{HotW} \quad (4)$$

where D_{El} is annual electricity demand, including the electricity required for lighting, appliances, hydronic pumps, and fans (kWh/yr), D_{Heat} is the annual heating demand minus the total heat recovered (i.e., the sum of the heat recovered by the supply-exhaust ventilation system and the heat recovered by the exhaust air heat pump) (kWh/yr), and D_{HotW} is the annual heat demand for hot water (kWh/yr).

To calculate the net energy demand, the model must be fed with the input parameters for each of the *representative buildings* (Table 3). These parameters include data on the building geometry and thermal properties of the construction materials, as well as the characteristics of the building service systems and required indoor temperature. In addition, each of the representative buildings has to be assigned a weighting coefficient, which represents the fraction of buildings in the entire stock that belong to that building category. The weighting coefficient allows the extrapolation of the results for the representative buildings to the entire stock. The *representative buildings* can be provided as sample buildings or archetypes. *Sample buildings* are herein designated as representing actual buildings (for data obtained from measurements). *Archetype buildings* are described theoretically from data collected from national statistics and reports about the overall characteristics of the buildings, as well as information about the region under study.

Table 3. Representative-building input parameters to the model for characterisation of the energy use in the building stock.

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	-

Therefore, the model is designed so that the inputs are can be readily collected from various sources in the different EU Member States. The authors have investigated and collected data in the form required for the model presented in the present work for Sweden, France, Germany, Spain and UK. The current literature indicates that similar data are available for the USA and Belgium [5, 14]. In addition, a common European approach (TABULA) has recently been developed for deriving building typologies, and an example of application to the Hellenic building stock is available [28]. Nonetheless, certain assumptions have to be made, e.g., regarding U-values and ventilation rates in relation to the age of the building, depending on the quality of the data available in the different Member States [14].

Each building has to be assigned to a certain location or climatic zone, as the investigated region may have to be subdivided into different climatic zones. Increasing the number of climatic zones increases considerably the computational time required for the modelling. The total number of climatic zones can be limited by adopting the climatic zones listed in the building regulations in the investigated country. The hourly values for climatic data required by the model are: outdoor temperature (ºC); global solar irradiation of horizontal surfaces (W/m^2); diffuse irradiation of horizontal surfaces (W/m^2); and normal direct irradiation (W/m^2). The weather parameters are arranged in a weather file, which has to be created according to the structure described in the International Building Physics Toolbox [29].

Energy saving measures assessed

The potential reduction in energy demand that could be achieved through application of the ESM is calculated in two ways: *individual* and *aggregated*. In the *individual* case, the measures are applied one at a time, to elucidate the potential energy saving from each measure. However, these potentials cannot be added together to obtain the overall effect of the measures. In the present study, the individual approach serves only as an initial assessment of the cost efficiency of each of the measures investigated. In the *aggregated* approach, several measures are applied simultaneously, given that the effects of one measure can influence other measures. Although the measures may be grouped in different ways, to date only aggregation according to annual costs of the measures (as obtained from the individual approach), in increasing cost order, has been investigated by the authors.

The number of measures is not predetermined in the model, which leaves open the possibility for assessing any measures that entail a change in one of the inputs listed in Table 3. Changes in some of the inputs would imply measures that are purely technological, i.e., replacement of a part of the building or its systems by a more energy-efficient component/system (e.g., changes in the average U-value of the envelope or changes in the efficiencies of the heat recovery systems or hydro pumps). However, changes in other inputs also involve non-technological measures (i.e., behavioural changes). For instance, a reduction in the use of hot water is considered to arise from substitution of the existing taps with aerator taps, although it also requires adequate operation by the occupants; a similar scenario applies to a reduction in electricity usage for lighting. While measures that include changes in the heating system (such as replacement of the existing system with a more efficient one) or fuel switching can be assessed in terms of delivered energy and CO_2 emissions, this issue has not been included in the analysis.

3.2 Delivered energy

The net energy, as presented in the previous section, has to be met by technical systems installed in the building. To meet the net energy demand, a specific amount of energy needs to be delivered to the building (*via* different energy carriers). Therefore, *delivered energy,* also commonly termed *final energy*, refers to the energy paid for by the consumers and supplied to the buildings; it includes losses within the buildings but excludes external conversion and transformation losses.

Delivered energy is usually the parameter for which data are available in the statistical databases [30, 31]. For this reason, delivered energy is used to validate the results of the modelling as applied to an entire country. In addition, delivered energy is required to estimate the levels of CO_2 emissions. The delivered energy is derived from:

$$E_{Delivered} = E_{Tot}/\mu \tag{5}$$

where E_{Tot} is the net energy demand, as obtained from Equation (4), and μ is the overall (weighted-average) efficiency of the energy conversion equipment and apparatus used for the delivery or production of space heating, hot water, and electricity for lighting and appliances.

The value of μ is calculated from:

$$\mu = \omega_{Heat} \cdot \mu_{Heat} + \omega_{Cool} \cdot \mu_{Cool} + \omega_{El} \cdot \mu_{El} + \omega_{HotW} \cdot \mu_{HotW} \quad (6)$$

where ω-s represents the weighting coefficients derived by dividing the net energy demand in Equation (4) by E_{tot}. For example, the weighting coefficient for space heating is given by:

$$\omega_{Heat} = D_{Heat}/E_{tot} \quad (7)$$

Equation (7) applies to a case in which a single energy carrier is used for the production or delivery of heat for space heating. If more than one energy carrier (fuel mix) is used, the net energy demand D_{Heat} should be split between the energy carriers, $D_{Heat,i}$, and the corresponding weighting coefficient is calculated from:

$$\omega_{Heat} = \sum_i D_{Heat,i} / E_{tot} = \sum_i \omega_{Heat,i} \quad (8)$$

where *i* denotes the energy carrier.

Some practical problems may arise when calculating the value of μ. While the data for the efficiency of electrical lighting and appliances, μ_{El}, are usually available, the efficiencies of the energy conversion equipment and apparatus for the delivery or production of space heating or hot water are typically not readily available. Whenever possible, the separate values of μ_{Heat} and μ_{HotW} should be calculated. However, in cases of combined production of heat for space heating and hot water, it is not straightforward to define the precise efficiency levels of each of these energy carriers. Instead, the same mix of energy carriers is assumed for both space heating and hot water provision, and a common μ_{Heat_common} value is assigned. Finally, if the information about the energy carriers used in the building is incomplete, i.e., the sum of the known percentages of the fuel shares is <1, the remaining percentage is assigned a value corresponding to the average efficiency of the known fraction of energy carriers.

Carbon dioxide emissions associated with the energy demand in the building stock are deduced by applying the emission factors for the different energy carriers to the energy delivered, as obtained from the modelling.

3.3 Costs

The annual energy saving cost (€/kWh-saved) is calculated from:

$$Cost_E = {}^{NAC_{EA}}/_{ES} \tag{9}$$

where NAC_{EA} is the net annual cost of the ESM (€/yr), and ES is the energy saved due to the application of the ESM (kWh/yr). The CO_2 avoidance cost, $Cost_{CO2}$ (€/tCO_2-avoided), is calculated from [32, 33][2]:

$$Cost_{CO2} = {}^{NAC_{EA}}/_{SEm} \tag{10}$$

where SEm is the reduction in CO_2 emissions due to the application of the ESM (tCO_2/yr). The net annual costs of implementing the ESM are given by [34, 35][3]:

$$NAC = EAC - S \tag{11}$$

$$EAC = \left({}^{C \cdot r}/_{1 - (1+r)^{-n}} \right) + M \tag{12}$$

where EAC is the equivalent annual cost, i.e., the annual cost of the investment required to apply the ESM over its entire lifetime (€/yr), S is the annual cost of the energy saved (€/yr), C is the investment cost of the ESM (€), r is the discount rate (0-1), n is the depreciation time for the ESM (yr), and M is the extra maintenance cost of the ESM (€/yr).

An ESM is considered to be cost-effective when the cost saving associated with its application exceeds the total cost for the ESM, i.e., when the energy-saving cost is negative (or the CO_2 avoidance cost is negative where emissions are concerned).

The *net annual costs* of the ESM (EAC in Equation 11) are defined according to the inputs listed in Table 4. The cost of a specific ESM, C, can be provided in € per heated area, in € per surface to be retrofitted, or in € per dwelling. The model user should decide what items to include in the cost of the ESM. Further studies are needed to decide on ways to include detailed features, so as to model separately the different components of the costs of ESM that represent the reality of achieving the calculated potentials.

Table 4. Input parameters required in the model to calculate the cost of energy-saving measures.

Description	Unit	To be provided
Interest rate	%	Per measure
Lifetime of the measure over which the annual cost saving is supplied	years	Per measure
Cost per heated area	€/m^2	Per measure
Cost per surface below ground to be retrofitted (basements)	€/m^2	Per measure
Cost per surface above ground to be retrofitted (facades)	€/m^2	Per measure
Cost per surface of roof/attic to be retrofitted	€/m^2	Per measure
Unitary cost	€/unit	Per measure
Average surface of an apartment dwelling	m^2	Per building
Surface of the building envelope below ground (basements)	m^2	Per building
Surface of the building envelope above ground (facades)	m^2	Per building
Surface of the building envelope corresponding to roof /attic	m^2	Per building

4 VALIDATION

The accuracy of the energy balance model (in Simulink) has been validated using comparative and empirical methods [36]. In the comparative validation, the modelling results for an office building located in Barcelona, Spain, and for a residential building in Köping, Sweden, were compared to the results from models that have been validated using the standard BESTest procedure [37]. Specifically, for the Swedish residential building, the calculated heat demand was found to be in good agreement (1% difference) with the values calculated using HAM-tools [see model validation in 38] [24]. Regarding the Spanish office building, the calculated heat demand was also in a good agreement with the values calculated using DesignBuilder/EnergyPlus [see model validation in 39]. In addition, the results for indoor temperature obtained in the present work were compared with those obtained for the Spanish building during a warm week, using DesignBuilder. As DesignBuilder allows detailed simulation of natural ventilation, it provided hourly based results that were closer (i.e., in terms of the amplitude and phase of the indoor temperatures) to the measured values than those provided by the model use in the present work. These discrepancies in the results for the amplitude and phase of the indoor temperatures between the ECCABS model and the measured temperatures can be attributed in part to uncertainties regarding some of the input values, given the characteristics of the building (i.e., large glass facades, ventilated basement, natural ventilation, and extensive exposure to the sun), and also by the fact that the cooling demand is covered exclusively by natural ventilation. Nevertheless, the average temperature values obtained with the two models were similar (26.1°C with ECCABS and 26.3°C with DesignBuilder).

In the empirical testing, the results of the model were compared with carefully obtained experimental data for the above-mentioned buildings. For the Swedish residential building, the calculated annual heat demand (101.6 kWh/m^2) was found to be in good agreement with the measured values (97.4 kWh/m^2), corresponding to a difference of <1% [24].

With respect to the modelling of entire building stocks, Sweden offers the unique resource of input data from 1,400 buildings derived from a field study in which these buildings were selected to represent the Swedish residential building stock [40]. There was a 5% difference between the (delivered) energy use of the Swedish residential sector, as given in the statistical datasets [30, 31], and the corresponding total energy use, as obtained from the modelling, and recalculated as delivered energy (as explained in Section 3.1. the results of the model relate ESMs to a baseline energy use, year Year 2005 in the Swedish case; while the statistics only report delivered energy). Thus, the baseline net energy demand is considered to be validated. The results from the modeling show that 71% of the total energy demand of the Swedish residential buildings is linked to heating, 10% to hot water provision, and 19% to electricity (for lighting, appliances, and cooking). In the present study, the data used for hot water demand are based on those provided in a recent study on the use of hot water in Swedish households [41]. Whereas the Odyssee database [30] indicates a larger share of the hot water demand (23%), there is no clear explanation as to about how this higher value was derived.

5 APPLICATION OF THE MODEL

As mentioned above, the Swedish housing stock was used as a study case for developing the methodology [27]. Table 5 shows the net annual energy demand for the Swedish residential sector in Year 2005 (the reference year) given by the model. The net annual energy demand data are disaggregated into single-family dwellings (SFD), multi-family dwellings (MFD), and as totals for the residential sector. The values for delivered energy are lower than those for net energy demand, due to the extensive use of heat pumps in Sweden.

Table 5. Specific annual net energy demand and delivered energy by end-use (kWh/m^2) in the Swedish residential sector in Year 2005, as obtained from the present modelling methodology.

	Net energy demand			Delivered energy		
End-uses	**SFD**	**MFD**	**Residential**	**SFD**	**MFD**	**Residential**
Space heating	156	96	130	144	94	122
Hot water	16	19	17	15	18	16
Lighting and appliances (including cooking)	30	36	33	30	36	29
Total	202	150	179	189	147	170

SFD: Single-Family Dwelling; MFD: Multi-Family Dwelling.

Table 6 shows the modelling results for delivered energy per fuel used. For the reference year, electricity and district heating appear as the two major sources of delivered energy in residential buildings in Sweden, followed by biomass fuels. These results are in accordance with those in the statistical database [30].

Table 6. Energy demand by end-use and by fuel (TWh/yr) in the Swedish residential sector in Year 2005, as obtained from the present modelling.

Annual delivered energy							
Entire Residential Stock	**Electricity**	**Oil**	**Gas**	**Biomass**	**District Heating**	**Other**	**Total**
Space heating	18.4	2.8	1.0	11.0	29.6	2.7	65.5
Hot water	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: single-family dwelling; MFD: multi-family dwelling.

Regarding the assessment of ESM, 12 different measures (Table 7) were assessed. The annual energy demand of the Swedish residential sector could be reduced by 55% by applying all of the assessed ESM aggregated, while the sum of the individual potentials (given in Figure 1) reveals a total reduction potential of 63%. Figure 1 gives the individual contribution from each measure to the total reduction in energy demand and in CO_2 emissions as obtained from the model. The ESM that give the greatest savings are those involving heat recovery systems (i.e. measures 5 and 6 give a 22% reduction potential). A reduction of 1.2ºC in the average indoor temperature (down to an average of 20ºC), would save 14% of the energy use in dwellings. Upgrading of the U-value of cellars/basements and of facades (different types) and the replacement of windows would provide savings of about 7% for each action.

Table 7. Energy-saving measures assessed in the present work

Measure	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 SFD
6	Upgrade of ventilation systems with heat recovery, for apartment buildings MFD
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 SFD
10	Reduction in power used for the production of hot water to 1.10 W/m^2, for MFD
11	Replacement of hydro pumps by more efficient ones
12	Decrease in indoor air temperature to 20°C

SFD: single-family dwelling; MFD: multi-family dwelling.

The levels of CO_2 emissions from the Swedish building sector could be reduced by 63% by applying all the ESM studied. However, the levels of emissions from the Swedish building sector are already low (10% of total emissions), and reductions in CO_2 emissions are costly (per ton of CO_2 avoided). Therefore, emission reduction is not likely to be the main impetus for imposing energy efficiency measures in Sweden. Some specific ESM such as 50 % reduction of power for lighting and appliances (measures 7 and 8), increase CO_2 emissions since the production of the electricity saved is less CO_2-intensive than the fuel mix used for space heating.

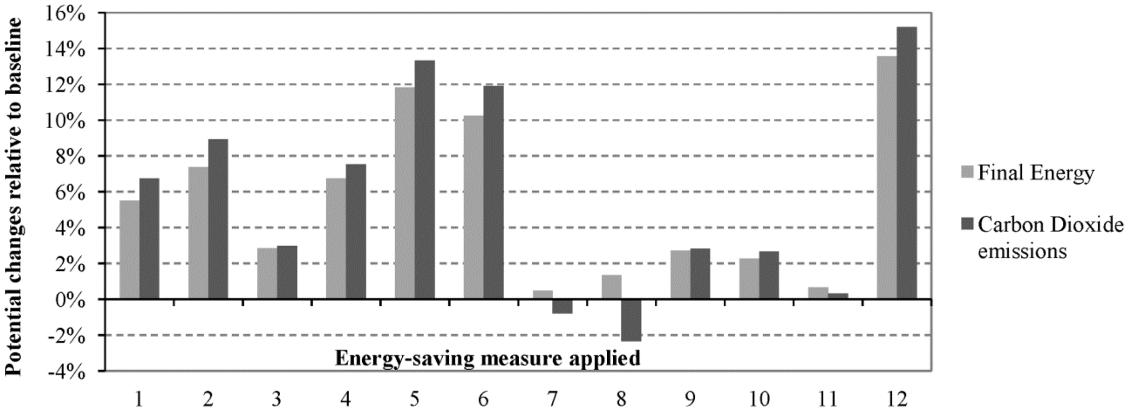

Figure 1. Relative changes in final energy and CO_2 emissions in the Swedish residential stock as obtained from the model, given as percentage of the baseline value for each ESM studied. See Table 7 for descriptions of the ESM.

Finally, Table 8 illustrates the results of the cost assessment conducted in the model. The first row (*All*) shows the average results for all the ESM considered, while the subsequent rows give the individual values for four selected measures, which include the retrofitting of: (1) basement walls; (2) facades; (3) roofs; and (4) window replacement. For instance, the average *equivalent annual cost* EAC of all the measures considered is 360 €/building. For this annuity, an average of 3900 kWh (SE) could be saved per building, translating into 63.2 TWh ($Total\ SE$) in savings for the entire country. This would result in an average energy saving cost $Cost_E$ (which includes the cost of the energy saved) of -0.04 €/kWh/yr (i.e., an annual saving of 0.04 €/kWh). In the Swedish residential stock, 21.4 TWh/yr could be saved in a cost-effective way (*Cost-Effective Potential* SE). The costs derived in the present model are the direct costs from a consumer perspective, which means that while one cannot expect that all the ESM identified as being cost-effective will be implemented, the results define the maximum potential for what one could expect from the ESM applied.

Table 8. Weighted averages of annual costs per building, as obtained from the model for selected ESM for the Swedish residential stock, at Year 2005 energy prices (see Table 7 for a description of the ESM).

Measures	EAC €/yr	SE kWh/yr	Total SE TWh/yr	SEm tCO_2/yr	Total SEm $MtCO_2/yr$	$Cost_E$ €/kWh/yr	Cost-effective* Potential SE TWh/yr
All	360	3900	63.2	0.22	3.50	-0.04	21.4
1	1200	5870	5.3	0.37	0.35	0.28	0.4
2	1100	5820	7.2	0.39	0.50	0.34	0.1
3	200	2130	2.7	0.10	0.10	0.13	0.7
4	440	4230	6.5	0.26	0.40	0.05	1.0

* Cost-effective: with a negative energy saving cost, $Cost_E$, as defined in Equation (9).

The modelling procedure developed in the present work should be applicable to other countries. In the present study, the Swedish residential building stock is used as a case for developing the methodology. However, the simplified one-zone model used for the buildings in this work may not be adequate for certain countries. For instance, in southern European regions, the climate may require either more active operation of buildings to maintain a continuously comfortable temperature (especially if applying passive systems such as natural ventilation) or the maintenance of different thermal zones within the same building. In addition, further work is needed to include latent loads in the calculation of the cooling demand.

Another simplification made in the present modelling is that the climate is assumed to be the same in the future as it is in the baseline year, i.e., the effects of anthropogenic climate change are not considered. It is assumed that this simplification does not have a decisive impact on the results, although further work is needed to verify this assumption. In addition, the assessment only takes into account the operating phase of buildings, which means that the construction and demolition phases are not considered. In the case of the existing stock, the implementation of ESM results in increased use of materials and necessitates disposal of the replaced materials; these actions are not accounted for in the model itself. More work is needed to include these phases and to include the co-benefits of ESM implementation.

The outcomes of modelling future emissions from the buildings obviously depend on assumptions made regarding the development of the entire energy system. Therefore, the present model should be viewed as a way of examining possibilities for emission reductions from building stocks under different scenarios in the future rather than as a means for making predictions (cf. [3]). More work is needed to investigate the effects of the model sensitivity results on input variations.

The successful application of the presented model has encouraged the authors to continue using and developing this model. In this respect, the model has been used in combination with a top-down econometrical model and a bottom-up engineering distribution model [42] to provide an overall assessment of energy efficiency and CO_2 mitigation strategies in the existing European building stock under different scenarios up to Year 2050 [43].

6 CONCLUSIONS

The bottom-up building physics model presented here allows assessments of the effects of energy-saving measures in building stocks. The model is based on a one-dimensional building energy balance, which gives hourly net energy demand. The model is formulated so that the results can be extended to an entire building stock (represented by a relatively high number of buildings) in terms of net energy demand, final energy, associated CO_2 emissions, and costs to implement the ESM.

The accuracy of the model has been validated by empirical and comparative means for selected buildings, with satisfactory results. In addition, the model has been applied to the Swedish residential stock represented by sample buildings. The resulting energy use levels show good agreement with the values in the statistical database. A noteworthy outcome is that application of the assessed energy-saving measures would reduce the energy use of the

Swedish residential sector by 55% and the associated CO_2 emissions by 63%.

It is concluded that the modelling procedure represents an efficient tool for studying the effects of energy-saving and CO_2-mitigation strategies in the building stocks of regions or countries, laying the groundwork for policy discussions. Further studies are needed to investigate the applicability of the model to countries other than Sweden. In addition, the assessment could be broadened to include future climate change, construction and demolition phases, a more detailed assessment of how to achieve the calculated potentials, and ways to generate results that reflect the uncertainty in the assumptions.

7 ACKNOWLEDGEMENTS

This work is financed by the AGS project Pathways to Sustainable European Energy Systems. Vahid M. Nik and Björn Mattsson are gratefully acknowledged for their contributions to the model development linked to the BETSI project.

8 REFERENCES

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

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

[3] S. Natarajan, J.Padget, L. Elliott, Modelling UK domestic energy and carbon emissions: an agent-based approach, Energy and Buildings 43 (2011) 2602-2612.

[4] D. Ürge-Vorsatz, Novikova, A., Köppel, S. and 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.

[5] Y.J. Huang, J. Brodrick, A bottom-up engineering estimate of the aggregate heating and cooling loads of the entire building stock. In: Proceedings of the 2000 ACEEE summer study on energy efficiency in buildings, Pacific Grove, 20–25 August, 2000.

[6] R. Ramirez, F. Sebold, T. Mayer, M. Ciminelli, M. Abrishami, A building simulation palooza: the California CEUS project and DrCEUS. IBPSA, Ninth international conference, August 15 – 18, 2005, Montreal, Canada.

[7] B. Griffith, D. Crawley, Methodology for analyzing the technical potential for energy performance in the U.S. commercial buildings sector with detailed energy modeling. SimBuild conference IBPSA-USA, 2006, Cambridge, Massachusetts.
[8] H. Farahbakhsh, V.I. Ugursal, A. Fung, A residential end-use energy consumption model for Canada, International Journal of Energy Research 22 (1998) 1133–1143.
[9] C.A. Balaras, K. Droutsa, A.A. Argiriou, and D.N. Asimakopoulos, Potential for energy conservation in apartment buildings. Energy and Buildings 31(2000)143–54.
[10] C. A. Balaras, K. Droutsa, E. Dascalaki, S. Kontoyiannidis, Heating energy consumption and resulting environmental impact of European apartment buildings, Energy and Buildings 37 (2005) 429-442 .
[11] F. Nemry, A. Uihlein, C. Makishi Colodel, B. Wittstock, A. Braune, C. Wetzel, I. Hasan, S. Niemeier, Y. Frech, J. Kreißig, N. Gallon, Environmental Improvement Potentials of Residential Buildings (IMPRO-Building). European Commission, Joint Research Centre, Institute for Prospective Technological Studies, 2008.
[12] C.A Balaras, K Droutsa, A.A Argiriou, K Wittchen, Assessment of energy and natural resources conservation in office buildings using TOBUS, Energy and Buildings 34 (2002) 135-153.
[13] E. Dascalaki, C. A. Balaras, XENIOS—a methodology for assessing refurbishment scenarios and the potential of application of RES and RUE in hotels, Energy and Buildings 36 (2004) 1091-1105.
[14] H. Hens, G. Verbeeck, and B. Verdonck ,Impact of energy efficiency measures on the CO2 emissions in the residential sector, a large scale analysis, Energy and Buildings 33 (2001) 275–81.
[15] L.D. Shorrock, J.E. Dunster, The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock , Energy Policy 25 (1997) 1027-1037.
[16] G.V. Fracastoro, M. Serraino, A methodology for assessing the energy performance of large scale building stocks and possible applications, Energy and Buildings 43 (2011) 844-852.
[17] D. Johnston, A physically based energy and carbon dioxide emission model of the UK housing stock. Ph.D. thesis. Leeds Metropolitan University, UK; 2003.
[18] M. Hinnells, B.Boardman, R. Layberry, S. Darby, G. Killip. 2007. The UK Housing Stock 2005 to 2050: Assumptions used in Scenarios and Sensitivity Analysis in UKDCM2. Report. Environmental Change Institute, University of Oxford.IDAE.
[19] S.K. Firth, K.J. Lomas, A.J. Wright, Targeting household energy-efficiency measures using sensitivity analysis, Building Research & Information 38 (2010) p. 25
[20] SGSR, Modelling Greenhouse Gas Emissions from Scottish Housing: Final Report. Scottish Government Social Research, Cambridge Architectural Research, Cambridge Econometrics, Roger Talbot & Associates Ltd, Alembic Research, 2009.
[21] Eceee. 2010. Policy brief on the recast Directive on buildings energy performance (EPDB) 2010/131/EU. European Council for an Energy Efficient Economy (eceee), Stockholm, Sweden.
[22] M. Levine, D. Ürge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling, H. Yoshino, 2007. Residential and commercial buildings. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, NY, USA.
[23] MathWorks, MATLAB r2008a. The MathWorks, Inc., Massachusetts, U.S.A., 2010.
[24] É. Mata, and A. Sasic Kalagasidis, 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, 2009. Available at: http://publications.lib.chalmers.se/records/fulltext/122325.pdf

[25] I. Sartori, B.J. Wachenfeldt, and A. G. Hestnes, , Energy demand in the Norwegian building stock: Scenarios on potential reduction, Energy Policy 37 (2009) 1614-1627.

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

[27] É., Mata, A. Sasic, and F. Johnsson, Energy usage and potential for energy saving measures in Swedish households (2012), submitted for publication.

[28] E. G. Dascalaki, K. G. Droutsa, C. A. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock, Energy and Buildings 43 (2011) 3400-3409.

[29] A. Sasic Kalagasidis, et al. (2006). ENLOSS testing with HAM-Tools. SMHI Common exercise 0. Calculation of energy use for space heating, Report 2005:6, Chalmers University of Technology. Gothemburg, Sweden, 2006.

[30] Enerdata, ODYSSEE database European Energy Efficiency Indicators NRDLINK 4.1 (SP1), Enerdata, Grenoble, France, 2010. Available at: http://www.odyssee-indicators.org/database/database.php

[31] EC, Eurostat Database, European Commission (EC), Brussels, Belgium, 2010.

[32] M. De Villiers, and K. Matibe, Greenhouse Gas Baseline and Mitigation Options for Residential Sector. Energy and Development Research Centre, University of Cape Town, Cape Town, 2000.

[33] L. Höglund-Isaksson and R. Mechler The GAINS Model for Greenhouse Gases - Version 1.0 : Methane (CH4) IIASA Interim Report IR-05-54, 2005.

[34] L.D. Shorrock, J. Henderson and J.I. Utley, Reducing carbon emissions from the UK housing stock. Housing Centre, BRE Environment. BRE Press, Garston, Watford, 2005.

[35] J. A. Clarke, C. M. Johnstone, J. M. Kim, and P. G. Tuohy, Energy, Carbon and Cost Performance of Building Stocks: Upgrade Analysis, Energy Labelling and National Policy Development, Advances in Building Energy Research 3 (2009) 1-20.

[36] R. Judkoff, J. Neymark, International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method, NREL, Colorado, 1995.

[37] ANSI/ASHRAE 140-2007 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs.

[38] A. Sasic Kalagasidis, C. Rode, M. Woloszyn, HAM-Tools – a whole building simulation tool in Annex 41. IEA Annex 41 closing seminar, Proceedings of the IEA ECBCS Annex 41 Closing seminar, Copenhagen (2008) 21-37.

[39] R. H. Henninger, M. J. Witte, EnergyPlus Testing with ANSI/ASHRAE Standard 140-2001 (BESTEST) EnergyPlus Version 1.1.0.020, Ernest Orlando Lawrence Berkeley National Laboratory Berkeley, California for U.S. Department of Energy, Washington, D.C., 2003.

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

[41] Energimyndighet, Mätning av kall- och varmvattenanvändning i 44 hushåll - Delrapport i Energimyndighetens projekt Förbättrad energistatistik i bebyggelsen och industrin, ER 2009:26, Statens energimyndighet, Eskilstuna, Sweden, 2009. (in Swedish)

[42] F. Johnsson (Ed.) AGS, Methods and Models used in the project Pathways to Sustainable European Energy Systems, AGS, Mölndal, Sweden, 2011.

[43] F. Johnsson (Ed.) AGS, European Energy Pathways - Pathways to Sustainable European Energy Systems, AGS, Mölndal, Sweden, 2011.

[1]Computer used: CPU-Intel Core2 Quad Q9550 2.83 GHz, 1333/12MB s-775, 160-GB hard disk, (7200v/8MB) SATAII.
[2]Only those studies in which Equation 10 is clearly stated are mentioned.
[3]Only those studies in which Equation 11 is clearly stated are mentioned.