THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Energy Efficiency and Carbon Dioxide Mitigation in Building Stocks

Development of methodology using the Swedish residential stock

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Department of Energy and Environment
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Abstract

This thesis investigates the implementation of energy-saving measures (ESM) in existing building stocks from an energy systems perspective. The effects of the measures are assessed in terms of net and delivered energy levels, carbon dioxide (CO_2) emissions, and the costs for implementing the measures. For this assessment, a bottom-up engineering energy balance model was developed that facilitates modelling of an entire building stock, i.e., the Energy, Carbon and Cost Assessment for Building Stocks (ECCABS) model. The model was validated by modelling a residential building in Sweden and an office building in Spain, and by comparing the results from the model developed in this work with measurements and with the results from a detailed heat balance model. The simplified model gives satisfactory results. When the model was applied to 1400 buildings representative of the Swedish residential building stock, the results showed good agreement with the available statistics on energy use in the Swedish residential building stock.

Application of the investigated ESM would reduce the net energy demand of the Swedish residential sector by 55%. The measures that would provide the greatest savings are installation of heat recovery systems (22%) and reduction of the indoor temperature (14%). The modelling results indicated that the upgrading of the U-value of basements and the U-value of facades and the replacement of windows would provide an annual energy saving of about 7% each. The net potential reductions in CO_2 emissions arising from the implementation of the ESM would be low, since the energy supply in Sweden generally associated with low levels of CO_2 emissions. In addition, measures that reduce the electricity for lighting and appliances would increase CO_2 emissions, since the electricity saved is less CO_2-intensive than the fuel mix used for the corresponding increase in space heating.

The model is also applied to evaluate the profitability of ESM for the Swedish residential stock under different scenarios for the development of the energy system, particularly with respect to the prices of energy carriers used as fuels in the buildings. Three scenarios were investigated: a baseline scenario that assumes a continuation of the present trends in energy use and associated CO_2 emissions, and two climate change mitigation scenarios.

Already in the baseline scenario, energy use could be reduced by 30% by implementing profitable ESM, whereas the climate change mitigation scenarios generate only modest increases in profitable energy reduction in spite of higher energy prices. The most profitable ESM are the same in all three scenarios and they involve: (1) a reduction by 50% of electricity for lighting and appliances; (2) a reduction of indoor temperature down to 20ºC; and (3) heat recovery for single-family dwellings. In contrast, the modelling reveals that the replacement of existing hydro-pumps with more efficient ones and the retrofitting of the building envelope are the most expensive ESM. The three scenarios give similar average annual costs for the ESM for the period 2010-2050. However, it cannot be expected that all of the cost efficiency potentials described in this thesis will be seized. Thus, further work is required to investigate how the energy-saving potentials identified in this work can be implemented.

Keywords: energy saving measure, Swedish building stock, bottom-up building modelling, techno-economic cost-effectiveness, buildings energy use

List of papers

The thesis is based on the following appended papers:

I. **ECCABS model: Energy, Carbon and Cost Assessment for Building Stocks**

É. Mata, A. Sasic Kalagasidis and F. Johnsson. Submitted for publication.

II. **The Swedish residential building stock: current and future energy use**

É. Mata, A. Sasic Kalagasidis and F. Johnsson. Submitted for publication.

III. **Costs of retrofit measures in Swedish residential building stock – an evaluation for three scenarios on future energy prices**

É. Mata, A. Sasic Kalagasidis and F. Johnsson. In: Proceedings of the 9th Nordic Symposium on Building Physics. 29th May - 2nd June 2011 Tampere, Finland.

Érika Mata is the main author and responsible for the modelling of Papers I, II & III. Filip Johnsson and Angela Sasic Kalagasidis have contributed to the discussion and editing of all papers. Other publications by the author, which in part overlap the content of this thesis and hence have not been included in the thesis, are:

i. **Quantifying the Energy Efficiency Gap for Space and Water heating in the Residential Sector in Sweden**

E. Ó Broin, É. Mata, J.Nässen and F. Johnsson. In: eceee 2011 Summer Study, 6–11 June, 2011, Belambra Presqu'île de Giens,, France.

ii. **Future end use energy demand in the European building stock.**

A. Göransson, E. Ó Broin, É. Mata. Chapter 44 in: European Energy Pathways. Pathways to Sustainable European Energy Systems, pp. 345-352. ISBN/ISSN: 987-91-978585-1-9

iii. **Energy efficiency strategies in the residential building stock.**

É. Mata, F. Johnsson and A. Sasic Kalagasidis. Chapter 45 in: European Energy Pathways - Pathways to a Sustainable European Energy System, pp. 353-361. ISBN/ISSN: 987-91-978585-1-9

iv. **A bottom-up model for energy, carbon and costs assessment of building stocks.**

É. Mata, F. Johnsson and A. Sasic Kalagasidis. Chapter 14 in: Methods and Models used in the project Pathways to Sustainable European Energy Systems, pp. 107-111. ISBN/ISSN: 978-91-978585-2-6

v. **Calculation of the energy use in the Swedish housing. Description of the building energy simulation model: ECCABS Energy Assessment of Building Stocks.**

   É. Mata, A. Sasic Kalagasidis and F. Johnsson. Report A 2010-01, ISSN 0281-0034, Chalmers University of Technology, Gothenburg, Sweden, 2010.

vi. **Retrofitting measures for energy savings in the Swedish residential building stock – assessing methodology**

   É. Mata, A. Sasic Kalagasidis and F. Johnsson. In: Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference, ISBN 978-1-933742-89-2, December 5-9, 2010, Florida, USA.

vii. **Assessment of retrofit measures for reduced energy use in residential building stocks– Simplified costs calculation**

   É. Mata, A. Sasic Kalagasidis and F. Johnsson. In: Ponencias Congreso SB10mad.Revitalización y Rehabilitación sostenible de barrios, ISBN 978-84-614-1920-3, Sustainable Building Conference SB10mad, April 28-30, 2010, Madrid, Spain.

viii. **Calculation of the energy use in the Swedish housing. Description of the building energy simulation model: EABS Energy Assessment of Building Stocks.**

   É. Mata and A. Sasic Kalagasidis, Report 2009:4, ISSN 1652-9162, Chalmers University of Technology, Gothenburg, Sweden, 2009.

Contents

Notations

A	Floor area	m^2
A_{temp}	Heated floor area (the floor area to be heated to more than 10 ºC limited by the inner side or the envelope)	m^2
BOA	Residential floor area (total area of the dwellings, excluding common areas (e.g. staircases) and area occupied by walls)	m^2
C_{HS}	Effective volumetric heat capacity of a heated space (whole building)	J/K
C	Investment cost of the measure	€
$Cost_E$	The annual saving cost	€/kWh
$Cost_{E_{NPV}}$	Weighted net present value of the annual saving cost for the whole time period assessed	$€_{2005}$/kWh
$Cost_{CO2}$	CO_2 avoidance cost	€/tCO_2
D_{Cool}	Annual heating energy demand for space cooling	kWh/yr
$E_{Delivered}$	Delivered energy	
D_{El}	Annual electricity demand, including the electricity required for lighting, appliances, hydronic pumps and fans	kWh/yr
D_{Heat}	Annual heating energy demand for space heating	kWh/yr
D_{HotW}	Annual heating energy demand for hot water production	kWh/yr
E_{tot}	Total Net Energy Use	kWh/yr
$(E_{tot})_0$	Total Net Energy Use in the baseline year	kWh/yr
EAC	Equivalent annual cost (the annual cost of the investment required to apply the measure over its entire life)	€/yr
ES	Energy saved due to the application of the measure	kWh/yr
n	Depreciation time for the energy saving measure	yr
N	Years to be discounted from the investment year back to the baseline year	yr
NAC_{EA}	Net annual cost of the efficiency measure	€/yr
M	Extra maintenance cost of the efficient alternative	€/yr
q	Total heat provided by the heating/cooling system	W
Q_{App}	Annual consumption of electricity for the operation of domestic appliances	kWh/yr
Q_{Fan}	Annual consumption of electricity for the operation of ventilation fans	kWh/yr
$Q_{HeatR\ FVP}$	Annual heating energy recovered by FVP	kWh/yr
Q_{HyP}	Annual consumption of electric energy for the operation of hydronic pumps	kWh/yr
q_{int}	Total internal heat gains	W

Q_{Lig}	Annual consumption of electric energy for the operation of electric lighting	kWh/yr
Q_{Occ}	Annual heating energy generated by people	kWh/yr
q_r	Solar radiation gains through windows	W
Q_r	Annual heating energy due to solar radiation gains through windows	kWh/yr
q_t	Transmission heat losses through a building envelope	W
Q_t	Annual transmission heat losses through a building envelope	kWh/yr
q_v	Ventilation heat losses (sanitary and natural)	W
Q_{vSa}	Total heating energy losses due to sanitary ventilation	kWh/yr
r	Discount rate applied to the investment cost C	0-1
R	Discount rate applied to the energy saving cost $Cost_E$	0-1
S	Annual cost of the energy saved	€/yr
T_{int}	Indoor air temperature	ºC
Tr_{min}	Minimum desired indoor temperature	ºC
T_v	Set point temperature for natural ventilation	ºC
SEm	Reduction in CO_2 emissions due to the application of the measure	tCO_2/yr
μ	Weighted-average efficiency of the energy conversion equipments and apparatus for delivery or production of space heating, hot water and the electricity for lighting and household appliances	0-1
μ_{Cool}	Weighted-average efficiency of the energy conversion equipments and apparatus for delivery or production space cooling	0-1
μ_{El}	Weighted-average efficiency of the energy conversion equipments and apparatus for delivery or production the electricity for lighting and household appliances	0-1
μ_{Heat}	Weighted-average efficiency of the energy conversion equipments and apparatus for delivery or production space heating	0-1
μ_{Heat_common}	Weighted-average efficiency of the energy conversion equipments and apparatus for delivery or production space heating and hot water	0-1
μ_{HotW}	Weighted-average efficiency of the energy conversion equipments and apparatus for delivery or production hot water	0-1
ω_{Cool}	Weighting coefficient representing the percentage of cooling demand in the total demand	0-1
ω_{El}	Weighting coefficient representing the percentage of electricity demand for lighting and appliances in the total demand	0-1
ω_{Heat}	Weighting coefficient representing the percentage of heating demand in the total demand	0-1

ω_{HotW}	Weighting coefficient representing the percentage of hot water demand in the total demand	0-1

Abbreviations

ADEME	Environment and Energy Management Agency [*Agence de l'Environnement et de la Maîtrise de l'Energie*, in French]
AGS	Alliance for Global Sustainability
AP	Appliances
BA	Baseline scenario
BETSI	Description of the existing buildings: technical characteristics, indoor environment and energy consumption [*Bebyggelsens Energianvändning, Tekniska Status och Innemiljö*, in Swedish].
BFR	Swedish National Council for Building Research [*Byggforskningsrådet*, in Swedish]
bw	Biomass/Waste
CI	Carbon intensity
CO	Cooling
CO_2	Carbon Dioxide
COP	Coefficient of Operative Performance
DB	Design Builder
DH	District Heating
EC	European Comission
ECCABS	Energy, Carbon and Cost Assessment of Building Stocks
el	Electricity
EOC	Environmental Objectives Council [*Miljömålsrådet*, in Swedish].
EP	Energy Price
ESM	Energy Saving Measure
EU	European Union
g	Gas
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GHG	Green House Gas
HW	Hot Water
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
LA	Lighting and Appliances (including cooking)
LI	Lighting
MA	Market scenario
MFD	Multi Family Dwelling

MURE	Mesures d´Utilisation Rationnelle de l´Energie
o	Oil
PO	Policy scenario
Res	Average Residential dwelling
SEA	Swedish Energy Agency [*Energimyndigheten*, in Swedish]
SFD	Single Family Dwelling
SH	Space Heating
UNECE	United Nations Economic Commission for Europe
VAT	Value Added Tax

1 Introduction

Climate change, security of energy supply, and competitiveness[1] in the energy market are all factors that underline the need to reduce energy use and green house gas (GHG) emissions from buildings. Towards these goals, legally binding targets to reduce energy use have been established in different countries. To meet these targets, existing technologies and systems are adequate (Pacala and Socolow 2004), at least for the next half-century (Hoffert et al. 2002), whereas clear and potent policy instruments are urgently required. In this context, understanding the potential roles and costs of different technologies is a prerequisite for the design of efficient policies. This is the topic of the present thesis, with focuses on improving the existing building stock.

While significant potentials for energy savings and mitigation of GHG emissions within the building sector in many countries have been reported (see Ürge et al. 2009 for a summary of potentials worldwide), these potentials have not been fully exploited. As a result, the levels of energy use and GHG emissions of, for instance, the European building sector continue to grow[2] (EC 2011; Enerdata 2010). In other words, despite the proven efficacy of energy-saving actions, large-scale implementation of such actions has not taken place.

As discussed below, a commonly expressed opinion in literature is that the failure to realise the potentials for energy savings is due to: (a) a lack of knowledge about the characteristics of the buildings; (b) a lack of awareness of the best steps to take for each building stock; and (c) the complexity associated with implementing energy-saving measures (ESM). An alternative viewpoint in the literature is that the potentials for energy savings are not seized upon because they are overestimated.

The lack of knowledge regarding the characteristics of the buildings (i.e., size, structure, and dynamics of change of the building stock) represents a major obstacle to investigations into how energy performance can be improved for the building stock. For instance, Kohler and Hassler (2002) concluded, using the German building stock as a case study, that most studies are strongly limited by the absence of reliable statistical data, and that international research confirms the global scale of this knowledge gap (Mistra 1997; IEA 2000). Similar conclusions have been reached by others (Balaras et al. 2007; Bradley and Kohler 2007; Pérez-Lombard et al. 2008; Dineen and Ó Gallachóir 2011). In a review of bottom-up building stock models for energy consumption in the residential sector and taking the UK building stock as an example, Kavgic et al. (2010) proposed an immediate solution in which models are supported by an annual publicly funded building and household survey that is representative of the stock and includes data on energy usage (preferably on at least a quarterly basis, so that seasonal variations, and thereby information on heating and cooling, can be deduced).

The main problem with identifying the best steps to take for improving building stocks is the lack of modelling tools. Although several studies have provided valuable information on how to evaluate ESM for a building stock (Ürge and Novikova 2008; Swan and Ugursal 2009; and Kavgic et al. 2010), they have applied modelling

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[1] A nation's competitiveness can be viewed as its position in the international marketplace compared to other nations of similar economic development (Önsel et al. 2008).

[2] In 2008 EU-15, wherein most of the countries had certain binding targets, had increased final energy consumption by 15% compared to 1990.

methodologies that are tailored to a specific region or to the conditions for which they were applied, and they are not readily accessible to other users. This means that the tools needed for a comprehensive assessment of the entire housing stock are not yet available, whereas user-friendly tools for energy assessments of individual buildings have already reached the market.

This thesis aims to develop a methodology that facilitates the assessment of ESM for building stocks. This methodology includes the development of an energy balance model that is based on a bottom-up engineering approach. In this methodology, the net energy demands of individual buildings are calculated from the physical and thermal properties of the buildings, including the heating and ventilation systems and climatic conditions. The model is used to investigate a list of ESM, including the retrofitting of the building envelope, the replacement of lighting and appliances, and the effects of reducing the indoor temperature.

The model is applied to a selection of buildings representative of the Swedish building stock. Subsequently, the results are scaled-up to represent the entire Swedish building stock. The resulting energy demand is converted into final energy and carbon dioxide (CO_2) emission savings using the efficiency factors for fuels and carbon intensity factors for fuels. Finally, the costs and gains obtained for the different ESM are calculated. Of special interest are those measures that are profitable, i.e., for which the direct cost of the measure is less than the cost of the energy saved by implementing the measure.

The work described in this thesis is linked to the international project *Pathways to Sustainable European Energy Systems* (hereinafter, the *Pathways Project*), which studies the ways in which the European energy system might be transformed so as to be more sustainable, with a special focus on meeting targets for energy efficiency, reductions in CO_2 emissions, and increased use of renewable energy (AGS 2011a). One of the aims of the Pathways Project has been to develop a modelling package to represent the European energy system, including a work package to analyse the building sector (AGS 2011b). In addition, the methodology has been developed and validated within the framework of a project to assess the Swedish building stock carried out by the Swedish National Board of Housing, Building, and Planning (*Boverket*, in Swedish) and is related to a large field investigation of the building stock, called the *BETSI Program* (BETSI 2009). The assessment included a quantification of the energy-saving potentials of existing residential buildings, based on data collected during the BETSI investigation on 1,400 sample buildings to which a number of ESM was applied. The aim of the assessment was to investigate the means and costs to achieve the Swedish target of reducing end-use energy consumption in the Swedish building stock by 20% by 2020 and 50% by 2050. The model has been demonstrated to be capable of assessing the effects of the measures and it forms the basis for the work presented in this thesis.

2 Scope of the thesis

The main objective of this thesis is to address the large-scale implementation of energy-saving measures in existing building stocks from an energy systems perspective. The measures studied include the retrofitting of existing buildings by means of different measures, both such which give a direct effect and such which require behavioural changes to give the desired effect, but exclude improvements in the transformation and distribution of the energy or fuel switching. The effects of the measures and the strategies through which they should be implemented are assessed in terms of net and final energy, CO_2 emissions, and costs. The implications for policy-making are also briefly discussed. In terms of GHG emissions, the work is restricted to CO_2, since it is the most abundant GHG in the atmosphere and can be readily defined and since it is the major GHG from buildings.

This thesis has two aims: (1) to develop, apply, and evaluate an assessment methodology; and (2) to quantify the effects of energy-saving and CO_2-mitigation strategies in terms of net energy, delivered energy, CO_2 emissions, and costs. The thesis is based on the three appended papers (Papers I–III). This summary serves to synthesise the results described in the papers, which means that it does not give a paper-by-paper description.

Chapter 3 gives an overview of the availability of data on building stocks, including the data required to assess the implementation of energy-saving measures in building stocks.

Chapter 4 describes the methodology used in this thesis, starting with a review of the existing assessment methodologies. Thereafter, the model developed within the work of this thesis is described. The model is explained in Paper I, and the latest cost calculations are provided in Paper III. Of the publications not appended to this thesis: Report viii describes the first version of the model (called the EABS model), which only included an energy assessment tailored to Boverket´s needs within the BETSI program; Paper vi describes how the model was extended to include carbon and cost assessments; Paper vii demonstrates a simplified method for cost calculations, which are essential in allowing the model to be used with available inputs for any building stock; Report v is a summary of all the features of the ECCABS model and is meant to be continuously updated to serve as a user manual; and Paper iv describes how the methodology has been tailored to the needs of the Pathways Project.

Chapter 4 also includes a case study of the Swedish existing residential stock, describing the data, the energy-saving measures investigated, and the different scenarios assessed.

Chapter 5 presents the key results from the work, and Chapter 6 comprises a discussion of some critical issues arising from this work. Finally, some conclusions are drawn in Chapter 7, and the possibilities for further research are listed in Chapter 8.

3 Building-stock data

3.1 Description of a building stock

To estimate the effects of changing conditions (such as applying certain energy saving measures ESM) within a building stock, it is necessary to define a specific building stock. For this, information is required on the function, size, and age of the stock.

Information on the building stock is gathered through two basic approaches:

- Through surveys, which have been used especially for residential buildings. An example is the survey conducted within the BETSI project in Sweden (Boverket 2009). Data from this survey have been included in Papers II and III. Surveys provide a wide range of information about buildings, including their technical characteristics, fuel usage, and occupant behaviours. Such information is required for the categorisation of the stock and is a requirement for the modelling of energy use in the building stock. As a consequence, the few countries that have assessed energy-saving and CO_2-mitigation potentials have conducted major surveys of their building stocks, e.g., in the UK (Shorrock et al. 2005), Scotland (SGSR, 2009), and Belgium (Hilderson et al. 2010).
- Through a census, i.e., the establishment of a register of new building construction statistics. This type of investigation provides only basic information on the stock, such as the number of buildings or area. Although such information is typically reported in national and international statistics (see Chapter 3.2), it is not sufficient for assessments of energy-saving and CO_2-mitigation potentials.

Individual billing data and sub-metering may also be available and can be used as complementary information for characterizing a building stock.

Building stocks are generally divided into residential and non-residential buildings (also known as the tertiary or commercial sector). In the residential sector, allocations of main and second residences and vacant units are difficult to follow up due to the constant transferring from one category to another (Wilhelmsen, 1982). However, the residential sector is generally better known that the non-residential sector because:

- There is a particular political interest in the residential sector, especially in social housing (Kohler and Hassler, 2002);
- The non-residential sector has generally only been documented for isolated buildings for technical or cultural reasons (public buildings, industrial monuments etc.), with the primary focus being on individual outstanding buildings that are perceived as works of art (Kohler and Hassler 2002);
- Shops and offices can be located in residential buildings, which means that they are difficult to control and enumerate;
- The classification of non-residential buildings is unclear, as described in Chapter 3.2.

A building stock can be described in terms of *sample buildings* or *archetypes*. Sample buildings are herein designated as representing actual buildings (for data obtained from measurements) and used as the input for modelling. As the building stock of a country consists of buildings with different characteristics, an extensive sample of the buildings is required in order to derive the thermal characteristics of the building stock. Thus, establishment of the sample requires significant efforts towards measuring and quantifying the parameters of the building sample. Archetype buildings provide an approximate description of the building stock. Archetype buildings are based on knowledge of the overall building characteristics of the region (e.g., age, size, construction materials, and house type) in combination with national statistics related to the building sector (e.g., energy use, climate). Archetype buildings are defined for a number of building types and are then used as the input for the heat balance (Swan and Ugursal, 2009). The modelling described in this thesis (Paper I) uses sample buildings as the input (when applied in Papers II and III), although the modelling procedure can also be conducted with archetype buildings as the input.

To represent the Swedish residential building stock, 1,400 sample buildings were designated as being representative of the stock (BETSI project).

3.2 Data requirements and availability

The data requirements for assessing energy-saving and CO_2-mitigation strategies depend on the type of modelling used. A summary of relevant buildings data required to analyse energy use in buildings across Europe is given by Ó Broin (2007). The list of input data required for the modelling in this work is given in Chapter 4.3.

Although this work uses Sweden as a case study to develop the modelling methodology, the availability of building data in other EU countries have been assessed in order to decide on how to design the modelling so as to be applicable to other countries. Data availability for Sweden is discussed in Chapter 4.4.1.

On the EU and international levels, three readily accessible databases provide data on the building sector and are updated on a regular basis (any evaluation of national databases is outside the scope of this work). The three databases, the main contents of which are summarised in Table 3.1, are:

- Eurostat (EC 2011), which is the official database of the European Commission, follows regulations and guarantees the quality of the results, on the bases of uniform standards and harmonised methods. Eurostat collaborates with the International Energy Agency (IEA) and the United Nations Economic Commission for Europe (UNECE), to collect statistical data from national authorities. Nevertheless, as evidenced by Table 3.1, the stored data are rather limited and are provided in a highly aggregated form. For instance, Eurostat does not provide information on the GHG emissions of the residential or tertiary sectors, only the total emissions for any given country.

Table 3.1. Summary of international data sources for the energy consumption levels and characteristics of the European building sector.

		Odyssee	**Eurostat**	**GAINS**
Years included	Units used	1980-2005	1990-2009	2005-30
Buildings' characteristics				
Stock of dwellings	k	Yes		Yes (1, 6)
Stock of dwellings (permanently occupied)	k	Yes(1)		Yes (1, 6)
Stock of dwellings with individual central heating	k	Yes(9)		
Stock of dwellings with room heating	k	Yes(9)		
Floor area of dwellings (total)	m^2			Yes (1, 6)
Floor area of dwellings (average)	m^2	Yes(1)		
Floor area of new dwellings (average)	m^2	Yes(1)		
Stock of refrigerators	k	Yes		
Stock of freezers	k	Yes		
Stock of washing machine	k	Yes		
Stock of dishwashers	k			
Stock of televisions	k			
Equipment rate of households (refrigerators)	%			
Equipment rate of households (freezers)	%			
Equipment rate of households (washing machines)	%			
Equipment rate of households (dishwashers)	%			
Equipment rate of households (televisions)	%			
Floor area of tertiary dwellings (total)	1000m	Yes(5)		
Buildings' energy consumption levels				
Total final consumption		Yes	Yes	
Coal consumption, residential sector	Mtoe	Yes(4)		
Oil products consumption , residential sector	Mtoe	Yes(3)		
Gas consumption, residential sector	Mtoe	Yes(3)		
Heat consumption, residential sector	Mtoe	Yes(4)		Yes(6)
Wood consumption, residential sector	Mtoe	Yes(4)		
Electricity consumption, residential sector	Mtoe	Yes(2)	Yes	Yes(2, 7)
Final energy consumption, residential sector	Mtoe	Yes(3)		
Final consumption, residential with climatic corrections	Mtoe	Yes		
Final consumption, tertiary sector	Mtoe	Yes(3)	Yes	Yes
Coal consumption, tertiary sector	Mtoe	Yes		Yes
Oil products consumption, tertiary sector	Mtoe	Yes		Yes
Gas consumption, tertiary sector	Mtoe	Yes		Yes
Heat consumption, tertiary sector	Mtoe	Yes		Yes
Wood consumption, tertiary sector	Mtoe	Yes		Yes
Electricity consumption, tertiary sector	Mtoe	Yes(5)		Yes(2, 8)
Final consumption, tertiary sector	Mtoe	Yes(5)		Yes
Total consumption, tertiary sector (climate corrected)	Mtoe	Yes		
Buildings' CO_2 emissions				
CO_2 emissions	$MtCO_2$	Yes(10)		Yes
Total CO_2 emissions (with electricity)	$MtCO_2$	Yes(10)		Yes

k= thousand units

(1)Data provided disaggregated into SFD and MFD.

(2)Data provided disaggregated into SH, HW, CO, LI, AP.

(3)Data provided disaggregated into SH, HW, CO.

(4)Data provided disaggregated into SH, HW.

(5)Data provided disaggregated into hotels/ restaurants, health and social actions, education/research, administration, private services, offices and trade (wholesale and retail).

(6)Data provided disaggregated into Existing and New.

(7)Data provided disaggregated into Cooling and Heating.

(8)Data provided disaggregated into Cooling, Heating and Ventilation.

(9)Only permanently occupied dwellings.

- ODYSSEE-MURE (Enerdata 2008) is co-ordinated by the French Environment and Energy Management Agency [*Agence de l'Environnement et de la Maîtrise de l'Energie,* ADEME] with the technical support of Enerdata and Fraunhofer[3]. The project relies on two comprehensive databases: ODYSSEE and MURE[4]. ODYSSEE contains detailed information on the energy consumption drivers by end-use and sub-sector, as well as energy efficiency and CO_2-related indicators. A network of national contributors updates the data regularly. The ODYSSEE database is managed by Enerdata and is updated twice a year. MURE is a database of policy measures.
- The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) database of the International Institute for Applied Systems Analysis (IIASA, 2010) provides a framework for the analysis of co-benefit reduction strategies for air pollution and greenhouse gas sources. This comprehensive dataset covers the following subsectors: (1) residential; (2) commercial and public services; and (3) other services, including agriculture, forestry, fishing, and unspecified subsectors. However, there is a lack of transparency regarding the input sources and the processes of data finding and extraction can be rather complex. Another drawback of this database is that when the detailed split of domestic energy consumption is not known, the total sector consumption may be reported under other services.

In addition to the above sources, some European projects and periodical reports have compiled all the information available on the building stock of a given country or set of countries. Ó Broin (2007) has mapped the available data, indicators, and models related to the energy demands of European buildings, providing a valuable review of these types of projects and reports. Pérez-Lombard et al. (2008) have reviewed the energy consumption data for buildings worldwide in the last 30 years (not in a continuous way but providing snapshots when the information was available).

In summary, the international statistical data are rather limited and for a bottom-up model like the one presented in Paper I, are only sufficient for the validation of the results obtained at an aggregated country level. Nevertheless, for top-down models, such databases, especially GAINS, may be more useful.

Finally, on the national level, the levels of data vary significantly from one country to another. The conclusions drawn from studies conducted in France (Gravalon, 2007; Martinlagardette, 2008) and Spain (Ràfols, 2008) are in agreement with the findings of this thesis on the following points:

- National statistics are sufficient to quantify the number of buildings and their areas.
- Reports from official entities responsible for dwellings (e.g., Ministry of Dwellings/Energy/Environment) provide information about the buildings' physical characteristics. However, it is much more difficult to find corresponding data for non-residential buildings.
- Regulatory codes are useful for determining the indoor conditions and thermal properties of the building envelope.

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[3] Fraunhofer-Gesellschaft, Munich, Germany, 2010. http://www.fraunhofer.de/en/contact-headquarters/index.jsp

[4] MURE Measures for a rational energy use [*Mesures d'Utilisation Rationnelle de l'Energie*, in French]. http://www.mure2.com/

Therefore, it is clear that the data available on the national level are sufficient to define the inputs required for a bottom-up model, such as the one presented in Paper I, provided of course that assumptions can be made when the data are incomplete or insufficient.

4 Methodology

4.1 Types of modelling methodologies

Models for analysing the effects and costs of energy saving measures (ESM) on entire building stocks under different assumptions for the future[5] should ideally:

a) estimate the 'baseline' energy consumption of the building sector disaggregated by different building categories and energy end-uses,

b) explore the effect of different energy saving measures with respect to costs and CO_2 emission reductions; and

c) not be confined to issues that are directly related to energy, but should be capable of assessing the effects of emission reduction strategies on indoor environmental quality[6] (Kavgic et al. 2010).

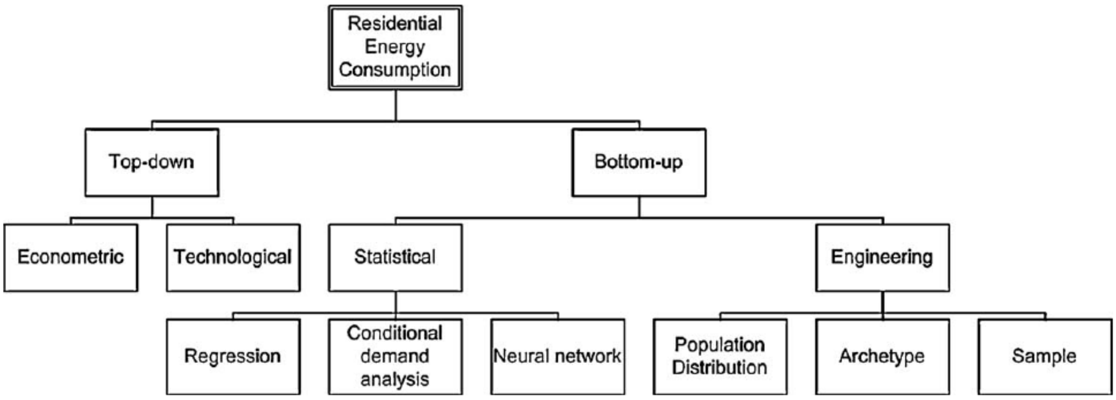

Figure 4.1 Top-down and bottom-up modelling techniques for estimating regional or national residential energy consumption. Source: Swan and Ugursal (2009).

Current techniques to model end-use energy consumption in the residential sector have been reviewed by Swan and Ugursal (2009). The available models can be divided into bottom-up and top-down models, as illustrated in Figure 4.1. The benefits and limitations of these modelling approaches are summarized in Table 4.1, with data from Swan and Ugursal (2009). Both approaches have been subjected to criticism based on the limitations summarised in the table. A third approach uses so-called *hybrid models*, which are models that combine the technological explicitness of the bottom-up approach with estimations of the consumer and firm behaviours of the top-down model approach (Jaccard 2004). Hybrid models have not been considered in any of the above-mentioned reviews. However, some examples of hybrid methodologies

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[5] Kavgic et al. (2010) uses the term '*Building stock models for energy consumption*' which herein is referred to as '*Models for analysing the effects and costs of energy-saving measures on entire building stocks under different assumptions for the future*'.

[6] This last condition is however out of the scope of the work of this thesis.

are available (Rivers and Jaccard 2005; Yang and Kohler 2008), and they provide more comprehensive assessments, including the beneficial features of both the top-down and bottom-up approaches.

Paper I compiles existing methodologies for the assessment of potentials and costs of CO_2 mitigation in buildings that are bottom-up or that are based on data from bottom-up studies, and Paper III focuses on methodologies for cost assessment.

Table 4.1. Benefits and limitations of the bottom-up and top-down modelling approaches (from Swan and Ugursal 2009).

	Top-down	Bottom-up statistical	Bottom-up building physics
Benefits	- Long-term forecasting in the absence of any discontinuity -Inclusion of macroeconomic and socioeconomic effects - Simple input information - Encompasses trends	- Encompasses occupant behaviour - Determination of typical end-use energy contribution - Inclusion of macroeconomic and socioeconomic effects - Uses billing data and simple survey information	- Models new technologies - Determines each end-use energy consumption by type, rating, etc. - Determines end-use qualities based on simulation
Limitations	- Less suitable for examining technology-specific policies - Typically assumes efficient markets and no efficiency gaps - Reliance on historical consumption information - No explicit representation of end-uses - Coarse analysis	- Relies on historical consumption data - Require a large sample - Multicollinearity - Relies on historical consumption information - Large survey sample to exploit variety	- Assumption of occupant behaviour and unspecified end-uses - Detailed input information - Computationally intensive - No economic factors considered

4.2 Choice of modelling approach

The development of the modelling methodology is a substantial part of this thesis, and it is facilitated by the linkages to the Pathways project and BETSI program. As indicated, the BETSI program focused on quantifying the effects on end-use energy consumption and energy savings of applying ESM and on estimating the costs to implement such ESM. The modelling of the building sector, according to the aims of the Pathways project, emphasises the energy system perspective. For both the objectives of the BETSI project and for the initial steps of the Pathways project (as illustrated in Figure 4.2), a bottom-up engineering approach was found to be suitable. Such modelling is based on calculation of the energy consumption of an individual building or groups of houses, including a detailed description of the building stock, associated systems, and with the results being extrapolated to represent an entire region.

Several bottom-up studies have provided valuable information on how to evaluate energy efficiency measures for a building stock. The studies that are considered relevant to the specific purpose of this thesis are reviewed in the *Introduction* to Paper I. In addition, the reviews of Ürge and Novikova (2008) and Kavgic et al. (2010) are useful in this respect. As discussed in Paper I, most of the models are not readily available or the methodologies are tailored specifically to the region for which they were developed. Therefore, the ECCABS model has been developed as a tool for the investigation presented in this thesis.

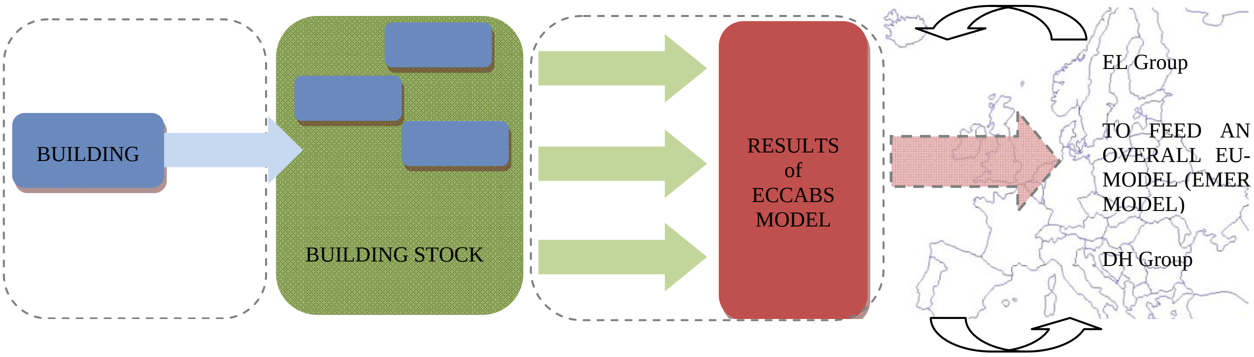


Figure 4.2 Overview of the modelling process as conceived for the Pathways project.

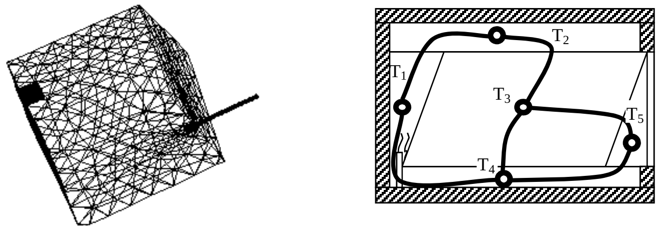
The development of the modelling in this work was performed according to the steps shown in Figure 4.2. In the first step, a simplified thermal model of a building was developed for calculation of the hourly values for indoor temperature and energy demand for heating and cooling in a single building. The model was compared with a detailed building physics model, to verify the simplified model. In the second step, the thermal model for the single building was upgraded with the routines for multiple data inputs and outputs so that the energy balance could be derived for a high number of buildings (representative of an entire building stock). The cost calculations for different ESM were also included at this stage. Finally, by varying the input data on ESM, different scenarios for the development of the energy system could be assessed with respect to the prices for energy and CO_2 emissions associated with the energy carriers used in the buildings.

The model is presented in Paper I, and is briefly summarised in the following Chapter.

4.3 The ECCABS Model

The Energy, Carbon and Cost Assessment of Building Stocks (ECCABS) model has been developed in the Matlab and Simulink environments (www.mathworks.com). The model consists of two parts: a Simulink model, which solves the energy balance for buildings; and a code written in Matlab, which handles the input and output data from the Simulink model. The net energy demand of individual buildings is calculated based on the physical and thermal properties of the buildings, a description of the heating and ventilation systems, and usage and climate conditions. The energy balance is calculated every hour and the results are summed to give the annual values. The model can be used with both sample and archetype buildings. Each building is treated as one thermal zone, as shown in the bottom-right panel of Figure 4.3. This simplified representation has been chosen for the following reasons:

- To reduce computational time.
- To facilitate data gathering. When the data that describe a building stock are difficult to find, reducing the input data make it more likely that efforts will be made to gather data in regions for which these data are lacking.
- To be coherent with respect to the approach. Since the buildings to be analysed have to represent a building stock, they are by definition created from average values. For instance, instead of simulating separately buildings that are predominantly exposed to each one of the possible orientations north, south, east or west, we assume that the buildings stock includes all possible orientations. Therefore, we simulate only one building.



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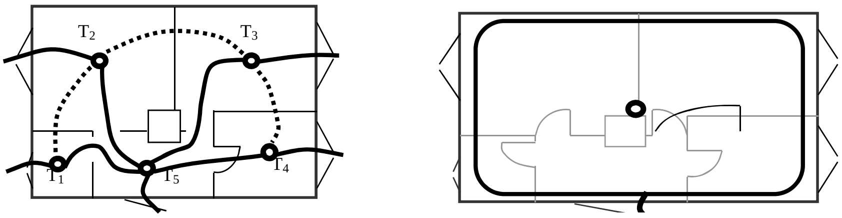

Intermediate

Coarse

Figure 4.3 Levels of modelling of indoor climate. Source: Monika Woloszyn, CETHIL, France.

The accuracy of the energy balance model (in Simulink) was tested and validated against the measured data for two buildings: an office building located in Barcelona, Spain (Mata et al. 2009), and a residential building in Köping, Sweden (Sasic Kalagasidis, 2006). For the Spanish office building, where the cooling demand is met by natural ventilation only, the indoor temperature during a warm week was calculated and compared to the measured indoor temperatures. The results were reasonable albeit not in full agreement with the measurements, due to uncertainties associated with 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), although the difference could also be due to the simplified modelling approach used. This latter may indeed be the case, since a more detailed simulation of the building using Design Builder (DB 2010), which generates a more detailed simulation of the natural ventilation, showed better agreement with the measured data. Nevertheless, the annual heating demand level obtained in the ECCABS model, 76.6 kWh/m^2, is within the range of measured heat consumption for similar buildings on the same campus, 49.6–85.4 kWh/m^2. As for the residential (Köping) building, the calculated annual heat demand was comparable to measured data: measured consumption in 2002 was 97.4 kWh/m^2, and the calculated demand for the same year is 98.2 kWh/m^2 (Mata et al. 2009). The process of model development is briefly described in Paper I, in which the model is described in detail. The most recent update of cost calculations from the model is given in Paper III.

Table 4.2. Summary of inputs and outputs in the ECCABS model (see Paper I for a detailed description of the inputs and outputs and their units).

Inputs	**Outputs**
Building stock description	*Net Energy demand by End-Uses(1)*
Area of heated floor space	
Total external surfaces of the building	Space Heating
Total window surface area of the building	Hot Water
Shading coefficient of the window	Electricity
Frame coefficient of the window	Total
Effective volumetric heat capacity of a heated space	
Coefficient of solar transmission of the window	
Average U-value of the building envelope	
Response capacity of the heating system	
Maximum power rating of the heating system	
Heat losses of the fan to the indoor air	
Specific fan power	
Efficiency of the heat recovery system	
Electricity consumption of hydro pumps	
Minimum indoor temperature	
Indoor temperature above which the opening of windows/natural ventilation is assumed to occur	
Initial indoor temperature	
Minimum ventilation flow rate (sanitary ventilation)	
Natural ventilation flow rate	
Average constant gain due to people in the building	
Average power demand for hot water production	
Fuel description	*Final Energy Use by Fuels(1) (2)*
Fuels used in each building type	Space heating
Efficiency of each fuel	Hot water
Carbon intensity of each fuel	Lighting
	Appliances
	Total
	CO_2 emissions associated(1) (2)
Costs description	*Cost assessment(1) (2) (4)*
Interest rate(4)	Equivalent annual costs, EAC
Lifetime of the measure over which the annual cost saving is supplied(4)	Cost of energy saved, S Energy saving cost, $\mathrm{Cost_E}$
Cost per heated area(4)	Abatement cost, $\mathrm{Cost_{CO2}}$
Cost per surface below ground to be retrofitted (basements) (4)	
Cost per surface above ground to be retrofitted (facades) (4)	
Cost per surface of roof/attic to be retrofitted(4)	
Unitary cost(4)	
Average surface of an apartment dwelling(2)	
Surface of the building envelope below ground (basements) (1)	
Surface of the building envelope above ground (facades) (1)	
Surface of the building envelope corresponding to roof /attic(1)	

(1)For each building type

(2)Data provided disaggregated into single-family dwellings (SFD) and multi-family dwellings (MFD)

(3)For each fuel type: Electricity, Oil, Gas, Biomass/Waste, and District Heating

(4)For each energy-saving measure assessed

The ECCABS model provides the following outputs: net energy demand by end-uses; and final energy demand (Table 4.2). As the results for net energy demand are not available in the statistics, the model provides a significant contribution to the description of energy use in a building stock. However, the final energy use of an entire country building stock, as listed in Table 4.2, might be more easily available from national statistics, although it is rarely available for other sizes of building stocks (e.g., for a housing company, a neighbourhood or a local region).

In addition, model outputs are provided per energy carrier, so that they can be used as inputs for further analyses in other models within the Pathways project (*cf.* AGS 2011). In particular, the ECCABS model is linked to other models in the Pathway project in the following ways:

- The energy use outputs of the buildings and market share of district heating (DH) from the ECCABS model are used to analyse the development of DH
- The outputs of delivered energy to the buildings from the ECCABS model are transformed into primary energy in the Pathway project and then used as inputs for other models in the project
- The outputs from modelling of the electricity generation sector are used as inputs to the scenarios for the building stock used in the modelling with ECCABS.
- The outputs from the modelling of energy market scenarios for the EU industrial sector are used as inputs in the scenarios for the building sector used in the model in the present work.

4.4 Case study: Sweden

As indicated above, the model was validated with data from the BETSI field study (Step 2 in Figure 4.2), in co-operation with the Swedish National Board of Housing, Building and Planning [*Boverket*, in Swedish].

In the 1990s, the investment costs and opportunities for energy efficiency in the Swedish building stock were calculated by the Swedish National Council for Building Research BFR [*Byggforskningsrådet*, in Swedish] (1996), using the MSA model (BFR 1984, 1987) for residential buildings and the ERÅD model (Göransson et al. 1992) for commercial buildings. BFR (1996) also discussed how the *techno-economic potential* [7] could be achieved up to year 2020, including new buildings yet to be built. However, these two models (MSA and ERÅD) are not readily available and could not be used in BETSI project.

In the BETSI study, Boverket wished to answer the following questions:

- What are the prerequisites for the current goals for the reduction of energy use in Sweden to be achieved through application of the suggested 23 ESM (as defined in Chapter 4.4.2)?
- What is the cost of meeting these goals?

Current goals for the reduction of energy use in Sweden, as stated in the program of the Swedish Environmental Objectives Council (EOC, 2009[8]) are: a 20% reduction in specific energy use by year 2020 and a 50% reduction by year 2050, compared to the

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[7] The *techno-economic potential* is the cost-effective (i.e., profitable) technical potential to reduce energy demand or CO_2 emissions.

[8] Environmental Objectives Council [*Miljömålsrådet*, in Swedish]. www.miljomal.nu

reference year 1995. To answer the questions posed above and given that the modelling methodologies previously used for the simulation of building energy use were no longer available, Boverket commissioned the Departments of Energy and Environment and Civil and Environmental Engineering at Chalmers to carry out a numerical investigation of energy-saving potentials in existing residential buildings, based on the sample buildings collected in the BETSI investigation, and requested a list of energy efficiency measures.

A part of the work presented in this thesis was developed within the framework of this co-operation between Boverket and Chalmers University.

4.4.1 Description of the Swedish building stock: the BETSI project

In Papers II and III, the Swedish residential building stock is described in terms of 1384 sample buildings, based on information gathered by Boverket in the BETSI project. Further details regarding how the buildings were selected and how the survey was performed are given in Paper II.

Before BETSI, several studies on the characteristics of buildings had already been carried in Sweden, namely ERBOL, ELIB, and STIL2. ERBOL was carried out in 1984-1985 as part of the Construction Research Council program EHUS-85, through a survey that included about 1500 housing units and offices in 62 municipalities. The report of Tolstoy and Svennerstedt (1984) describes structural design as well as the normal and extraordinary maintenance measures.

The ELIB program investigated the technical characteristics, energy use, and indoor climate of the Swedish residential stock in 1993. The National Institute for Building Research (SIB) inspected 1148 statistically selected buildings in 60 municipalities. There are several reports (SIB 1993[9]), but Report TN: 29 (Tolstoy et al. 1993) is particularly interesting because it deals with the characteristics of the residential buildings with respect to electricity, heating, ventilation, construction, and moisture damage.

The 2006 STIL2 study covers energy and assessments of the indoor environments of schools and preschools in Sweden. The study includes an inventory of the energy use and indoor environmental quality of 129 schools and kindergartens, as well as a questionnaire concerning perceptions of the indoor environment filled in by the staff at 105 of these schools (SEA 2007).

In summary, there has been continuous mapping and characterisation of the Swedish building stock, with respect to both the residential and non-residential sectors. Such detailed knowledge of the national building stock is very rare, and it has only been found for Belgium, Scotland and UK, as mentioned in Chapter 3.1. However, as conclued in Chapter 3.2, data from the BETSI project only serve to define the inputs for the sample buildings used in the model. The aggregated results for energy use obtained from the model have to be compared with data on the energy use in the entire Swedish building stock, which is found in national statistics and international databases.

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

Nevertheless, the data available in statistical databases do not always correspond with the data in BETSI. For instance, the size of the stock used in this work was collected within the BETSI program and is related to *heated floor area* (A_{temp}, in m^2), i.e., the floor area of spaces to be heated to more than 10ºC limited by the inner side of the envelope. BETSI used A_{temp} because it is the measure used in the mandatory building codes, and it is also the measure on which the Swedish Environmental Objectives Council (EOC 2009*)* is based. However, the official statistics (SBC 2011) give measurements of *residential floor area* (BOA, in m^2), which refers to the surface of the dwellings, excluding common areas (e.g., staircases) and wall thicknesses. This issue is discussed in detail in Boverket (2009). The Odyssee and GAINS databases (Enerdata 2010; IIASA 2010) report on total floor area BOA. These conflicting definitions in the available data sources explain the differences that will be found (in Section 6.1) when comparing the results of this work (as presented in Paper II) with the data obtained from the above-mentioned statistical sources.

4.4.2 Energy saving measures investigated

A list of 23 measures to be assessed was suggested by Boverket in the framework of the above-mentioned co-operation within the BETSI program. A detailed description of the measures is given in Boverket (2009).

Measures 1 to 17 and measure 22 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 behavioural changes. For instance, while a reduction in the use of hot water is considered to correspond to substitution of the existing taps with aerator taps, it also requires adequate operation by the occupants. The distinction between technical and behavioural measures is relevant because, for the technical measures, one can assume that the potentials will be fully achieved if the measure is applied, e.g., if the windows are replaced. However, for the measures that involve behavioural changes, it has to be discussed to what extent and how the potentials will be achieved even if the measure is applied. Such a discussion is outside the scope of this thesis.

Measures 1 to 5 involve the retrofitting of the parts of the building envelope below the ground (i.e., cellars and basements), and each of these measures reflects the same type of measure but applied to different types of cellars (floor above crawlspace, flat floor on ground, floor above unheated basements, basement wall above ground, basement wall below ground). Measures 6 to 8 consist of the retrofitting of the parts of the building envelope above the ground (i.e., facades), each referring to a different type of existing building construction detail for the facades (ventilated walls with different cover materials, brick facades). Measures 9 to 14 consist of the retrofitting of attics and roofs, and each measure refers to a different part of the attic/roof and/or a different type of existing constructive solutions (attic joists, knee walls, sloped roof, flat roof).

The costs for the different measures were provided in the form of *equivalent annual costs* (EAC), also referred to as *annuities*, for each of the buildings and ESM, with an interest rate of 4% and with the lifetimes defined in Boverket (2009). However, such detailed data for the measures and costs will not always be available, and in this work, it was possible to get a detailed breakdown only because there was access to the sample buildings.

As the aim of this thesis is to develop the methodology to reduce the number of inputs required for the ESM, measures 1 to 5 have been grouped into a general “retrofit of basement/cellars”, measures 6 to 8 have been grouped into a general “retrofit of facades”, and measures 9 to 14 have been grouped into a general “retrofit of attics/roofs”. For the calculation of the *equivalent annual costs*, the investment costs of implementing (i.e., installing and operating) the ESM have also been simplified to be a function of the heated floor area, the surface affected by the retrofit or per dwelling.

As a result, after the grouping, the list is reduced to 12 measures. Reducing the number of inputs will make it easier to apply the modelling methodology to other countries. The results presented in Papers II and III are in reference to these 12 measures.

A validation of the reduction in the number of measures is presented in Mata et al. (2010a). The validation consists of comparing the resulting energy saving potentials and costs obtained with the 23 measures with those obtained with the 12 measures.

Regarding the energy-saving potentials given in this work, it is important to point out that the potential energy savings relate to applying the ESM on an *individual* base and in an *aggregated* form. The individual potential savings are calculated by applying the ESM one-by-one according to the type of measure (i.e., only one at a time), to get information on the potential energy saving from each measure. However, these potentials cannot be added to obtain the overall effect from the measures. Although this methodology has been used in the literature (e.g., Farahbakhsh et al. 1998; Swan et al. 2008; Ramirez et al. 2005; Griffith and Crawley 2006; Larsen and Nesbakken 2004; Balaras et al. 2000; IDAE, 2003; Nemry et al. 2008, Clinch et al. 2001; Balaras et al. 2007), it is not correct, since such an approach runs the risk of overestimating the overall energy saving. In this thesis, the individual approach only serves as an initial assessment of the cost of each of the measures investigated. As for the main analysis, the measures are applied in aggregated form, since the effect of one measure may influence that of another measure. For the aggregation, the measures are applied according to their annual costs, in the order of increasing cost.

4.4.3 Scenarios assessed

In this work, a scenario is a description of a possible future development of the energy system in terms of energy prices and CO_2 emissions associated with the different energy carriers used in the buildings. Thus, a scenario should not be regarded as an attempt to forecast the future development of the energy market but rather as a tool to investigate the possibilities and costs for transforming the building stock, given different possible futures.

The scenarios used in the appended papers differ in the following aspects:

In Paper II, only one possible scenario is used, in which it is assumed that carbon emissions associated with the different energy carriers in the buildings are constant over the years and equal to those in year 2005. However, the trends observed in Sweden related to the evolution of energy prices are extrapolated. Specifically, 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 the 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. The estimated consumer energy prices for the period from 2008 to 2020 are based on data from BFR (1996). These data have been further expanded by Profu (2008), and now include the prices for electricity, district heating, oil, natural gas, and biomass. The resulting energy prices are higher than the baseline scenario used in Paper III but lower than any of the mitigation scenarios.

In Paper III, three scenarios are applied to the overall European energy system (AGS, 2011):

- The Baseline scenario extrapolates historical trends of increased energy use and associated CO_2 emissions.
- In the Market scenario, targets are set for CO_2 reduction without explicit targets for energy savings or renewable energy. It is then up to the market to find solutions to meet these targets. The major policy measure is a cost associated with emitting CO_2 and, as a consequence, the scenario assumes that the production of district heating and electricity will be essentially CO_2-free by 2050 (through fuel shifting, some energy efficiency measures, and the application of renewable energy sources and carbon capture and storage technologies).
- The Policy scenario is a policy-driven pathway for climate change mitigation, in line with current EU political goals. This means that there are not only targets for the reduction of CO_2 emissions, but also targets for energy savings and the use of renewable energy sources, which will be promoted through policy instruments. Thus, although there is a cost associated with emitting CO_2, certain levels of renewables and energy efficiency measures are imposed.

The implications of the scenarios for the residential sector are introduced in the model as annual average increases in energy prices of 0.7% in the Market scenario and 0.5% in the Policy scenario, resulting in energy prices that are on average 36% and 28% higher, respectively, in year 2050 than in the Baseline (for further details, see AGS 2011). Specifically, electricity prices for Sweden are taken from AGS (2011), while the prices set by the other energy carriers are based on data on the average EU values from Axelsson and Harvey (2010). Distribution costs and excise taxes are added from IEA (2009), and VAT rates for the residential sector are based on current rates (EC 2010). The average CO_2 emissions from electricity production in Sweden are taken from AGS (2011).

The results obtained for the case study presented in this section will be given in Chapter 5 and discussed in Chapter 6.

5 Key results from the papers

The results discussed in this Chapter are those presented in Papers I, II, and III. The results are not presented on a paper-by-paper basis, but are instead discussed according to the topic, whereby some of the results are taken directly from the papers while other results have been added during the construction of the thesis.

5.1 Energy usage in the Swedish residential stock

The results obtained from the modelling presented in Paper I allow characterisation of the energy usage in the existing building stock in Sweden, as shown in Paper II. In particular, data on net energy by end-use (Table 5.1) is not currently available from existing databases of statistics on building stocks

Table 5.1. Net energy by end-use in the Swedish residential sector in year 2005, resulting from this work.

	SFD	**MFD**	**Residential**
Heated floor area (Mm^2)	301.2	236.6	537.8
Number of buildings (k)	1887.6	165.8	2053.4
Net Energy demand by End-Uses (TWh/yr)			
Space Heating (SH)	47.1	22.7	69.8
Hot Water (HW)	4.7	4.4	9.1
Electricity for Lighting and Appliances (LA)	9.2	8.4	17.6
Total	**61.0**	**35.5**	**96.5**

Mm^2= million square meters, k= thousand units

SFD, single-family dwelling; MFD, multi-family dwelling

As presented in Paper II and listed in Table 5.1, the total *net energy demand* of the Swedish residential stock resulting from this work is 96.5 TWh/yr, 72% of which is attributed to Space Heating (SH) demand, 10% to Hot Water (HW) demand, and 18% to Electricity for Lighting and Appliances (LA) demand, including cooking. The annual specific net energy demand of an average single family dwelling (SFD) is 156 kWh/m^2 for SH, 16 kWh/m^2 for HW, and 30 kWh/m^2 for LA. The annual specific net energy demand of an average multi family dwelling (MFD) is 96 kWh/m^2 for SH, 18 kWh/m^2 for HW, and 36 kWh/m^2 for LA. No data could be obtained in literature regarding the net energy demand by end-uses, which means that a comparison with the results of this work shown in Table 5.1 is not possible.

The *final delivered energy* of the Swedish residential building stock in year 2005, as derived in this work, was 91.8 TWh/yr. Final energy demand incorporates fuel conversion that takes place within the building, as occurs in oil-fired boilers and heat pumps. Since there heat pumps are common in Sweden, having a (Coefficient of Performance) COP greater than one (e.g., around 3), the final energy demand (91.8 TWh/yr) is lower than the net energy demand (96.5 TWh/yr). The resultant final energy demand corresponds to the value given in the national statistics, as discussed elsewhere (Boverket 2005 and 2009).

Figure 5.1 illustrates the delivered energy (see Table 5.2) from this work, distributed by energy carrier for residential buildings in Sweden. For SFDs, more than half of the the demand for SH is met by electricity (direct electric heating and heat pumps), while district heating and biomass both contribute with 25% and oil and other fuels both contribute with 5% of the total delivered energy. These contribution percentages are very similar for HW. For MFDs, both the SH and HW demands are almost entirely met by district heating. The fuel shares calculated for the overall residential stock are shown in Figure 5.1, and they do not fully agree with the previously published values. This discrepancy will be discussed in the following paragraph.

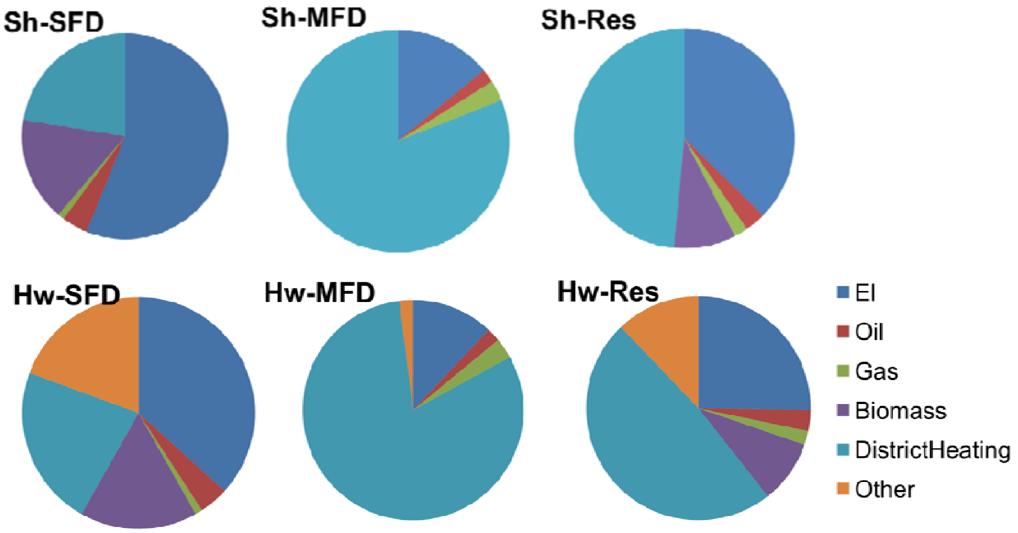

Figure 5.1. Delivered energy by fuel for end-use (SH, above; HW, below) for the Swedish residential stock as obtained in this work. Results are shown for SFD (left), MFD (middle), and the average for the overall residential stock (Res, right).

Table 5.2. Final energy by end-use by fuel (TWh/yr) in the Swedish residential sector in year 2005, as derived in the present work.

Fuel	Electricity	Oil	Gas	Biomass	DH	Other	Total
Residential	38.4	3.1	1.2	11.9	34.2	2.9	91.8
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
SFD	27.7	2.4	0.3	11.7	12.2	2.6	57.0
Space heating	16.5	2.2	0.3	10.8	11.2	2.3	43.3
Hot water	2.0	0.2	0.0	0.9	1.1	0.3	4.5
Lighting	1.9						1.9
Appliances	7.3						7.3
MFD	10.7	0.6	0.9	0.2	22.0	0.4	34.8
Space heating	2.0	0.5	0.7	0.2	18.4	0.3	22.1
Hot water	0.4	0.1	0.2	0.0	3.6	0.0	4.3
Lighting	1.7						1.7
Appliances	6.8						6.8

DH, district heating; SFD, single-family dwelling; MFD, multi-family dwelling.

Data that can be used for comparison with our results can be found in Enerdata (2010), which reports electricity, oil, biomass, and district heating shares for SHs of

37%, 10%, 18%, and 34%, respectively, and shares for HW of 29%, 10%, 15%, and 46%, respectively. A possible reason for the differences between these results and the results reported in this thesis is that the data used in this thesis for HW (which is required in the model as an input, in W/m^2) are based on a very recent study that measured water use in Swedish households (Swedish Energy Agency, 2009a), which showed that hot water usage was lower than previously reported. The Swedish Energy Agency (SEA 2009) has reported that the average hot water usage is 42 l/d per person in SFDs and 58 l/d per person in MFDs. The proportion of the total water volume used as hot water is 33% for SFDs and 32% for MFDs. As mentioned above, some studies for other countries report hot water usage levels higher than those considered in this study. For instance, hot water usage has been reported as 200 l/d per person for the USA (EM&RS 1994), 68–92 l/d per person for Russia (as design values), and about 85 l/d per person for Finland (Koiv and Toode 2006). Nevertheless, other studies have reported values similar to those considered in the present study; for instance, 46–85 l/d per person for the USA (NAHB 2002, reviewing sources dated from 1987 to 1998), 44 l/d per person for Estonia (Koiv and Toode 2006), and 50 l/d per person for the UK (DEFRA 2008). The usage levels are generally higher in the older studies, confirming more recent findings of a decrease in domestic hot water consumption with the increasing application of conservation measures, such as consumption measurements, renovation of domestic hot water systems, and installation of low-flow taps and showers (Bohm and Danning 2004; Koiv and Toode 2006).

Table 5.3. Specific annual delivered energy by end-use (kWh/m^2) in the Swedish residential sector in year 2005 (results from the present study).

End uses	SFD	MFD	Residential
Space heating	144	94	122
Hot water	15	18	16
Lighting	6	7	7
Appliances (including cooking)	24	29	22
TOTAL	189	147	170

SFD, single-family dwelling; MFD, multi-family dwelling

The *annual specific delivered energy demand in year 2005* of the residential stock (as derived in the present study) is 170 kWh/m^2, including 122 kWh/m^2 for SH, 16 kWh/m^2 for HW, 7 kWh/m^2 for lighting, and 22 kWh/m^2 for appliances (including cooking) (Table 5.3). This annual specific final energy demand is higher than the 150 kWh/m^2 reported by Boverket (2009); the reasons for this difference are not known. The annual specific final energy demand for single family dwellings (SFD) is 189 kWh/m^2, and for multi family dwellings (MFD) is 147 kWh/m^2. As shown in the modelling results by end use (Table 5.3), an SFD usually requires more energy for space heating, while an MFD generally requires more energy for hot water and appliances.

The *annual CO_2 emissions levels in year 2005* of the Swedish residential stock are presented in Paper II. As summarized in Table 5.4, the total annual CO_2 emissions of the Swedish residential stock correspond to 4.92 $MtCO_2$, of which 2.62 $MtCO_2$ is for SFDs and 2.29 $MtCO_2$ is for MFDs. The shares by fuel used are also given in Table 5.4. The emissions of the residential sector represent 10% of the 47.0 $MtCO_2$, which is reported to be the total annual emission level of the country (Enerdata, 2010).

According to the results presented in this thesis, an average Swedish SFD emits 1.39 tCO_2/yr, while an average Swedish MFD emits 0.81 tCO_2/yr, and an average residential dwelling emits 1.05 tCO_2/yr.

In summary, CO_2 emissions from the residential sector in Sweden are low due to the characteristics of its energy system. Thus, although energy efficiency measures are important for reducing energy use, the potential for using these as a means of reducing CO_2 emissions from Sweden is limited.

Table 5.4. CO_2 emissions ($MtCO_2$/yr) by fuel in the Swedish residential sector in year 2005 as obtained from this work.

Fuels	SFD	MFD	Residential
Electricity	0.41	0.16	0.57
Oil	0.66	0.17	0.83
Gas	0.13	0.36	0.49
Biomass	0.12	0	0.12
Coal	0	0	0
District Heating	0.86	1.54	2.40
Total	2.62	2.30	4.92

SFD, single-family dwelling; MFD, multi-family dwelling

5.2 Potential energy savings and CO_2 emissions avoided in the Swedish residential stock

Paper II reveals that the annual energy demand of the Swedish residential sector could be reduced by 53.4 TWh/yr (i.e., a 55% reduction) by applying all of the assessed energy saving measures (ESM) aggregated according to cost, i.e., the cheapest being applied first (as explained in Chapter 4.4.2). Table 5.5 shows the technical potential energy savings obtained for each ESM; the different measures generate savings of between 0.3 TWh/yr and 13.3 TWh/yr. The measures that give the greatest savings are those involving heat recovery systems (22% reduction), which is in agreement with previous results (Nilson et al. 1996). 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. This potential saving through window replacement is substantially lower than that previously reported (Nilson et al. 1996, Dalenbäck et al. (2005), and Sandberg 2007). The fact that the total energy saving potential for the Swedish residential sector is higher than that found in previous studies is discussed in Chapter 6.1.

The final energy saved by fuel per “individual” ESM studied (as defined in Chapter 4.3) is shown in Figure 5.2. For the measures that only would affect demand for space heating (measures 1 to 4, and 12), the contribution of the fuels to the energy saved (Figure 5.2) correspond to the average fuel mix for space heating of the dwellings in which the measure can be applied. For measure 5, upgrading of the ventilation with heat recovery implies a higher consumption of electricity (negative value in Table 5.6), since most SFD do not actually have a recovery system (or a mechanical ventilation system). However for measure 6, upgrading of the ventilation with heat recovery implies a reduction in electricity consumption. Since almost all MFD already have a ventilation system, measure 6 implies replacement of an old system with a new and more efficient one. When the electricity demand for lighting and appliances is reduced (measures 7 and 8), the heat released by the lights and appliances to the indoor air is also reduced, which means that the demand for space heating increases (i.e., negative values in Figure 5.2). Nevertheless taking into account both the increase in space heating demand and the reduction in electricity demand, the application of measures 7 and 8 results in energy savings. The ways in which the application of each ESM might affect the different fuels are shown in Table 5.6.

Table 5.5. Energy-saving potentials (TWh/yr) for the existing residential buildings in Sweden (data from the modeling in this work; see Paper II).

Measure No.	Description	Individual	Aggregated
	Total	**63.2**	**53.4**
1	Change of U-value of cellar/basement (different types)	5.3	4.4
2	Change of U-value of facades (different types)	7.2	6.1
3	Change of U-value of attics/roofs (different types)	2.7	2.3
4	Replacement of windows (U-value)	6.5	5.5
5	Ventilation with heat recovery (SFD)	12.0	10.2
6	Ventilation with heat recovery (MFD)	9.6	8.1
7	50% reduction of power for lighting	0.3	0.3
8	50% reduction of power for appliances	1.0	0.9
9	Reduction of power used for the production of hot water to 0.80 W/m2 (SFD)	2.6	2.2
10	Reduction of power used for the production of hot water to 1.10 W/m2 (MFD)	2.1	1.8
11	Change of electrical power to hydro pumps	0.6	0.5
12	Use of thermostats to reduce indoor air temperature to 20ºC	13.3	11.2

SFD, single-family dwelling; MFD, multi-family dwelling

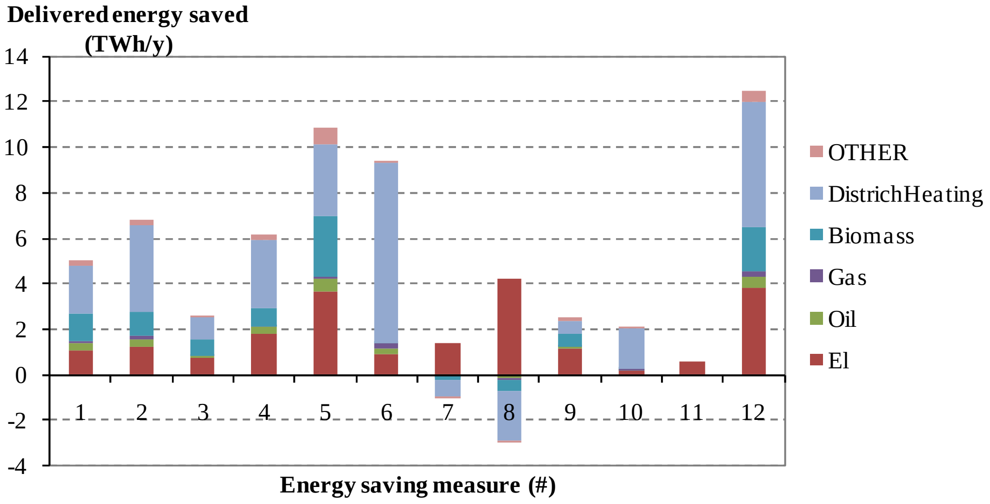

Figure 5.2. Final energy saved by fuel (TWh/yr, Y-axis) per each energy-saving measure studied (*x-axis*) for the Swedish residential stock (data from this work). The measures are represented by the measure number; a detailed description of each measure is given in Table Paper II.

Application of the ESM could potentially reduce the associated CO_2 emissions of the Swedish residential sector by 60%. However, the measures that would reduce the amount of electricity used for lighting and appliances (i.e., measures 7 and 8, having negative values in Figure 5.2) would increase CO_2 emissions because the saved production electricity would be less CO_2-intensive (assumed as Swedish electricity generation mix[10]) than the fuel mix used for space heating.

Table 5.6. Effects of selected ESM on net energy demand by end-use (TWh/yr) in the Swedish residential sector in year 2005 (Paper II).

Measure	Net Energy demand by end-use	SFD	MFD	Residential
5	**Space Heating**	12.74	0	12.74
	Hot Water	0	0	0
	Electricity	-0.78	0	-0.78
	Total	**11.95**	**0**	**11.95**
6	**Space Heating**	0	9.36	9.36
	Hot Water	0	0	0
	Electricity	0	0.25	0.25
	Total	**0**	**9.61**	**9.61**
7	**Space Heating**	-0.79	-0.65	-1.44
	Hot Water	0	0	0
	Electricity	0.95	0.83	1.78
	Total	**0.16**	**0.18**	**0.34**
8	**Space Heating**	-2.39	-1.97	-4.35
	Hot Water	0	0	0
	Electricity	2.84	2.48	5.31
	Total	**0.45**	**0.51**	**0.96**

SFD, single-family dwelling; MFD, multi-family dwelling

5.3 Costs of applying the ESM

The potential savings associated with the ESM, which are presented in Paper II and are given in Table 5.5, are related to the investment costs given by Boverket (as explained in Chapter 4.4.2). Investments amounting to €5.7 billion are required to achieve the aggregated *technical potential savings* of 53.4 TWh per year (assuming that all measures assessed in the present study are implemented), representing a 55% reduction in energy use in the residential sector. The current goals for the specific energy use in Sweden are expressed relative to the reference year of 1995. In the current work, year 2005 has been used as a baseline year because energy use in the residential sector in 1995 was almost the same as that in 2005 (EC 2011). As illustrated in Figure 5.3, an annual investment of €0.5 billion is required to meet the Swedish target for year 2020 (20% reduction in energy use compared to the level in 1995), and €3.5 billion Euro would have to be invested annually to achieve the 2050 target (50% reduction). For the 2020 target, the investment would correspond to €2 per m^2 and year, i.e., for a dwelling of 100 m^2, €200 would have to be invested annually until the year 2020. For the 2050 target and for the same dwelling, €1000 would have to be invested annually from now until the year 2050.

From the costs shown in Figure 5.3, the gains in saved fuel costs were subtracted to obtain the average *energy saving costs* (*$Cost_E$*) (Paper III). Thus, the weighted average energy saving costs for the ESM for the different scenarios could be derived (Table 5.7). The measures are ranked according to their increasing cost-effectiveness (i.e., an

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[10] Since this deals with reductions, the CO_2 emissions associated with electricity are those of the Swedish generation mix (which is almost CO_2 free).

ESM is *cost-effective* or *profitable* when the obtained energy saving cost ($Cost_E$) is negative) for the Baseline scenario (i.e., most cost-effective at the top of the table). The resulting ranking of the measures is very similar for all the scenarios. At the top of the ranking, a reduction by 50% in the level of electricity for lighting and appliances appears as a profitable measure (negative cost), as the investment cost is considered to be zero, given that soon there will be no other choice than to buy more efficient equipment. It is also profitable to reduce the indoor temperature because only the cost of the thermostats has been considered in this work. Finally, heat recovery is profitable for single family dwellings, which normally do not have a heat recovery system. In contrast, at the bottom of the ranking, the replacement of hydro-pumps with more efficient pumps and the retrofitting of all the parts of the building envelope (i.e., attics, basements, and facades) appear as the most expensive ESM.

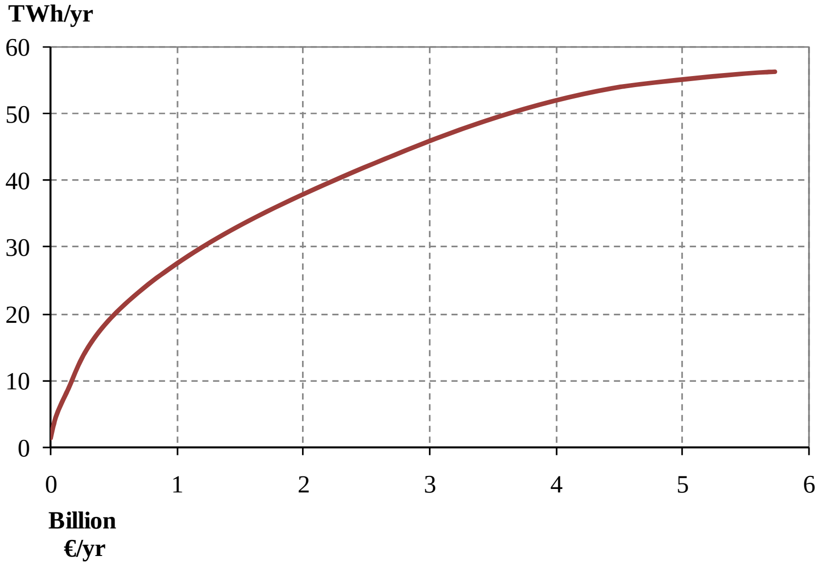

Figure 5.3. Relationships between annual investment levels required (*x*-axis) and potential energy savings (*y*-axis) for the Swedish residential stock according to the simulation results. The results used are from the modelling in this work.

Although the ranking of the investigated ESM is the same in the three scenarios, the average annual costs of the ESM differ, as can be seen from Table 5.7. An assessment for the period 2010-2030 (Mata et al. 2010b) gave an undiscounted average cost for the EMS investigated of €0.024/kWh/yr. This cost is higher than that described by Dalenbäck et al. (2005), who reported a potential of 26 TWh/yr with investments of SEK185 billion/yr, corresponding to an average of €0.014/kWh/yr (the discrepancies between the work of Dalenbäck and colleagues and the present work will be discussed in Chapter 6.1). An assessment conducted for the period 2010-2050 revealed an average net profit from application of the measures, as shown in Table 5.7.Thus, the average profit margins are: €0.020/kWh/yr for the Baseline scenario; €0.017/kWh/yr for the Market scenario; and €0.013/kWh/yr for the Policy scenario. These results are of course influenced by the assumed changes in energy prices.

Table 5.7. Average annual energy saving costs ($Cost_E$) of the measures per building (€$_{2005}$cents/kWh), for the period 2010-2050. A negative value represents a profit given the assumptions regarding interest rate and depreciation rate (Paper III)

Measure No.	Description	Baseline	Market	Policy
	Average of all ESM studied	-1.2	-1.7	-1.3
8	50% reduction in power for lighting	-15.4	-16.1	-14.7
7	50% reduction in power for appliances	-14.9	-15.5	-14.2
12	Use of thermostats to reduce indoor air temperature by 1.2ºC down to 20ºC	-3.5	-4.0	-3.9
5	Ventilation with heat recovery (SFD)	-0.4	-1.0	-0.9
9	Reduction of power used for the production of hot water to 0.80 W/m^2 A_{temp} (SFD)	0.2	-0.4	-0.2
10	Reduction of power used for the production of hot water to 1.10 W/m^2 A_{temp}[11] (MFD)	0.8	0.2	0.3
6	Ventilation with heat recovery (MFD)	1.0	0.5	0.5
4	Replacement of windows (U-value)	1.2	0.7	0.8
3	Change of U-value of attics/roofs (different	5.3	4.8	4.9
11	Hydro-pump replacement	10.0	9.5	9.7
1	Change of U-value of cellars/basements	12.4	11.9	12.0
2	Change of U-value of facades (different types)	16.0	15.5	15.6

SFD, single-family dwelling; MFD, multi-family dwelling

Assuming that only the profitable measures would be applied up to the year 2050, energy demand in the Swedish housing could be reduced by 30% in the Baseline scenario, by 42% in the Market scenario, and by 41% in the Policy scenario. However, as shown in Table 5.7, profitability is higher for the Market scenario.

The *average CO_2-abatement cost* is €300/tCO_2 (ranging from €-2900/tCO_2 to €7300/tCO_2), based on electricity production as a Swedish mix, i.e. very low CO_2 emissions (as given in Paper III) which results in high costs for some of the measures and buildings investigated. 95% of the CO_2 reduction potentials identified having a cost of less than €8400/tCO_2 and the CO_2 emissions of the Swedish residential sector could be reduced by 52% by applying measures profitable in terms of CO_2 (i.e., negative values for the abatement cost, $Cost_{CO2}$, as defined in Paper I). Details of the abatement costs are given by Mata et al. (2010b). Since there are almost no CO_2 emissions from the Swedish building sector, this thesis places little emphasis on CO_2 abatement (which clearly is not a driving force for energy efficiency measures in a Swedish context), which means that CO_2 abatement costs have not been calculated in Paper III.

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[11] Heated floor area (A_{temp}) is the floor area of spaces to be heated to more than 10ºC limited by the inner side of the building envelope. A_{temp} is the measure used in the mandatory building codes, and also is the unit used in the definition of the Swedish Environmental Objectives Council's (EOC 2011) efficiency targets.

6 Discussion

6.1 Potential energy savings and CO_2 emissions avoided

Several aspects of the calculations of the energy savings potentials warrant discussion. To start with, the modelling methodology (presented in Paper I) relates the energy efficiency measures to a baseline year energy use. One issue related to the baseline is that the climate data used in the simulations in Papers II and III correspond to average values for the years 1995-2005, while the energy measurements (from field measurements and statistics) are from year 2005. Since the aim is to estimate the potential energy savings, the accuracy of the baseline data should not be decisive, whereas the results compared to any baseline are valid as long as the climate data and overall assumptions are similar.

A second issue relates to the ventilation rates. The final energy demand of the Swedish residential building stock in year 2005 was 91.8 TWh/yr, as summarised in Table 5.2, and this was obtained using the ventilation rates described in the BETSI project. However, the values used as the input to the modelling for SFDs were lower than the 0.35 $l/s/m^2$ recommended by the Ministry of Health as the level required to ensure adequate indoor air quality. If the ventilation rate is increased to 0.35 $l/s/m^2$ in the modelling of the SFDs, the demand increases to 97.7 TWh/yr. Since it is reasonable to assume that adequate indoor air quality will be a requirement in the future, the energy demand for increased ventilation has been used as a baseline value to compare the potential energy savings presented in Chapter 5.2.

The resulting energy saving potentials rely on the assumptions, possible efficiency options and approaches made in the modelling (modelling approaches are discussed in Chapter 4.1). Consequently, comparison of the results obtained in this work with those of previous studies is not a straightforward task. First, there are several definitions of *energy saving potentials*. The total *technical potential*[12] presented in this thesis is up to 65% higher than the value reported by Sandberg (2007), while the *techno-economic potential*[13] saving presented in this thesis is 30%-50% lower than that previously reported (BFR 1996; Dalenbäck et al. 2005; Göransson and Pettersson 2008). Second, bottom-up modelling, as employed in this work, tends to give higher resulting potentials than top-down assessments (see Swan and Ugursal 2009 for a review of this issue). Third, the number of measures studied influences the total potential (e.g., some studies do not include reduced indoor temperature as an efficiency option). Fourth, the data used for the description of the building stock will influence the results. In this respect, the assessment presented in this thesis is the first based on a description of the Swedish buildings in 2005, while all the other studies are based on the Swedish building stock in 1995 (Boverket 1995). Therefore, the differences between the energy-saving potentials for Sweden reported in this thesis and those reported by others may be due to the above-mentioned factors. However,

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[12] The *technical potential* is defined as the amount by which it is possible to reduce energy demand or CO_2 emissions by implementing already demonstrated technologies and practices without specific reference to costs.

[13] The *techno-economic potential* is the cost-effective (i.e., profitable) technical potential to reduce energy demand or CO_2 emissions.

the influences of these factors on the resulting energy-saving potentials cannot be defined precisely.

6.2 Cost assessment

The profitability assessments in Paper III reveal that different future scenarios, such as the Market and Policy scenarios applied in this work (see Chapter 4.4.3), may not lead to significant differences in the profitabilities of the energy saving measures (ESM), as compared to the Baseline situation in which a 30% reduction in energy use could be achieved already through profitable ESM. Under the assumptions made in the Market and Policy scenarios, an annual increase of 0.7% in energy prices (Market scenario) would lead to a 12% reduction in energy use (compared to the baseline) if the profitable ESM were applied, while an annual increase of 0.5% in energy prices (Policy scenario) would result in an 11% reduction in energy use (compared to the baseline) if the profitable ESM were applied. However, profitability could be higher in the Market scenario (i.e., *profitability* as *average energy saving cost*, as shown in Table 5.7).

A sensitivity analysis of the modelling of the cost-effective energy savings was carried out by changing the energy prices in 0.5% increments from -2% per annum to 8% per annum (Figure 6.1). The price range was chosen based on the fact that the largest five-year energy price increase seen over the period of 1970 to 2005 was 8%. Already, when current energy prices persist (0%), there is a 22% reduction potential from cost-effective ESM. The reason that the curve in Figure 6.1 is not a straight line is that the allocation of energy-efficiency measures is not the same for the different cases modelled.

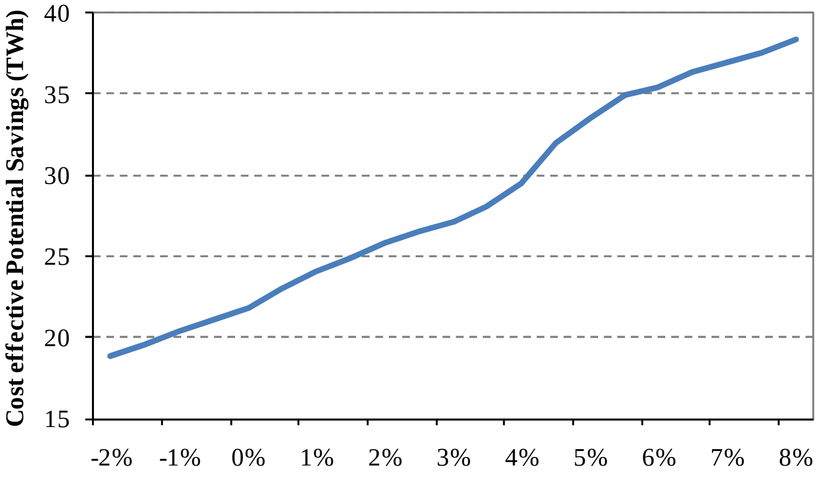

Figure 6.1. Potential savings derived from a sensitivity analysis of cost-effective energy savings under different price change scenarios (ranging from an annual decrease of 2% to an annual increase of 8% in price).

With respect to CO_2 abatement costs in the Swedish residential sector, as indicated above, the associated costs are high because emission levels are already low. As there are few studies on the topic, it is difficult to compare the results obtained with those of other groups. McKinsey (2008) assessed the greenhouse gas abatement opportunities in all sectors in Sweden up to year 2020. Since that study covers all sectors, the results for the Swedish residential stock only report on the retrofitting of existing buildings at a cost of €640/tCO_2e for "Multi-family homes retrofit 80 kWh/m^2" (without explaining what type of retrofitting is involved). This can be compared to the above-mentioned average value from this work, which is €300/tCO_2. In addition, the McKinsey report does not provide the methodology used or the specific measures included, which makes it difficult to draw any detailed conclusions from a comparison with the present work.

That the costs assessed in this thesis are only direct and viewed from a consumer perspective means that one can derive highly cost-effective potentials. There are differing opinions as to how to define and take into account the cost for implementation of ESM, and the calculation of direct costs is only one of the factors considered. For instance, the Directive on Buildings Energy Performance (EPDB) 2010/131/EU EPBD recast refers only to direct costs. The additional cost associated with implementing policy measures required to implement the ESM could be added to the direct cost, since each measure requires the application of a policy for the purpose of achieving one or more actions[14] necessary to implement the measure, as discussed in ERG (1998) and ILWG (2000). Several difficulties need to be overcome in order to calculate the cost of a policy. These include difficulties associated with; 1) finding case studies that provide quantitative information on the actual effects of implementing ESM; 2) evaluating the impact of a policy as an isolated single instrument; and 3) calculating the real cost-effectiveness of policies due to transaction costs, direct and indirect co-benefits, and possible negative side-effects. Nevertheless, recent studies that measure and report energy savings are promising and will help to quantify the costs associated with successful policies (IEA 2005; Ürge-Vorsatz and Koppel 2007; Ürge-Vorsatz et al. 2007; EMEEES 2009)

Several authors have tried to complement the direct costs, as obtained from bottom-up studies such as the present work, with an additional cost that reflects the various implementation factors, e.g., implementation costs (De Villiers and Matibe 2000), intangible capital costs (Jaccard and Denis 2005; EMRG et al. 2007), perceived private costs (MKJA 2002), expected resource costs (MKJA 2002), and transaction costs (Hein and Blok 1995; Ostertag 1999; Michaelowa and Jotzo 2005).

An alternative explanation for the difficulty experienced with getting cost-efficient measures implemented is that consumers tend to apply high discount rates to their investments, i.e., higher than those applied when calculating direct costs, as in this work. The discount rates implicit in consumer tradeoffs between initial energy-efficiency investment costs can be empirically measured, using for instance choice models of consumer durable goods (Newlon and Weitzel 1991; Train 2002; Jaccard and Denis 2005) or stated preference (Hausman 1979; Train 1985).

In summary, the costs derived in this work are the direct costs from a consumer perspective, which means that one cannot expect that all the ESM identified as being cost-effective will be implemented. Further studies are needed to decide on ways to include the implementation costs in this type of project.

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[14] *Action* is a change in equipment acquisition, equipment use rates, lifestyle choices or resource management that alters the net GHG emissions from what they otherwise would be (ERG 1998).

6.3 Modelling approach

A goal of this work was to find a methodology that could handle an entire building stock. Thus, the modelling of the buildings (presented in Paper I) has been simplified to require fewer input data than models that are applied for detailed energy evaluation of single buildings. In addition, the inherent assumptions of the model and the data used are transparent and documented in detail (available in reports).

The accessibility of the *sample buildings* for the Swedish building stock used to develop and verify the model (Papers II and III) is a core component of the work presented in this thesis. The model can also be applied to cases in which data for sample buildings are lacking, by first developing *archetype* buildings (as defined in Chapter 3.1), i.e., such buildings can also be used as the input in the present model.

As indicated previously, the modelling procedure developed in this work has the aim of being applicable to other countries, in that Sweden was merely used as a case for developing the methodology. The simplified one-zone model for the buildings applied in this work may not be sufficient for certain countries. For instance, in southern European regions, the climate may require more active operation of buildings to maintain a steady comfort temperature, especially if applying passive systems (e.g., natural ventilation), or it might require the maintenance of different thermal zones within the same building. Moreover, the simplification of the windows to one horizontal window may also have to be reviewed for regions and climates with strong solar radiation. Thus, there is always a trade-off between the extent to which the model can be simplified and ensuring that the model includes the most important features related to determining the energy balance of buildings representative for the region under investigation. In summary, the methodology developed within this work may need to be adapted to local conditions.

Another simplification made in the modelling is that the climate is assumed to be the same in the future as in the baseline year, i.e., the effects of anthropogenic climate change are not considered. It is assumed that this simplification do not have a decisive impact on the results, although further work is needed to verify this assumption. Moreover, changes in the energy system, such as improvements in the efficiencies of fuels or fuel switching, have not been considered. In addition, it should be noted that for some of the measures the expected technical life-time is rather long (e.g., 40 years) and the depreciation time has been set as being equal to the expected technical life-time. This is a major simplification, since a house-owner will most likely have a higher requirement regarding a return (pay-back time) on the investment made (see Chapter 6.2). Therefore, the present work is limited to an analysis of the direct costs that should define an upper potential for what one could expect from the energy efficiency measures applied.

The assessment only takes into account the operating phase of buildings, that is, construction and demolition phases are not considered. Thus, the model presented in Paper I is not designed to include building demolition or new construction, although this may be included in future versions. Consequently, the work presented in Papers II and III refers only to the existing stock. In the case of the existing stock, the implementation of ESM results in an increased use of materials and requires the disposal of the replaced materials, which are not accounted for in the model itself. In addition, as the energy for building operation decreases, the relative importance of the energy used in the production phase increases and influences optimisation aimed at minimising the life cycle energy use (see, for instance, Gustavsson and Joelsson 2010, for Swedish residential buildings). The inclusion of such phases might change the magnitudes of the potentials and the costs associated with their implementation.

In summary, the model methodology described in this thesis is a first attempt to establish a tool to quantify the effects of energy saving and CO_2 mitigation strategies for an entire building stock, laying the groundwork for discussions of policy implications.

7 Conclusions

The following conclusions can be drawn from the work performed in this thesis:

- A modelling methodology has been developed with the aim of assessing the value of energy-saving measures (ESM) for an entire building stock in terms of energy-saving potentials, as well as reductions in associated direct costs and CO_2 emissions.
- A number of ESM has been selected and applied to 1,400 sample buildings representative of the entire existing residential building stock in Sweden.
- The application of the selected ESM could reduce the final energy demand of the Swedish residential sector by 55%. The measures that provide the greatest savings are those that involve heat recovery systems and those that involve a reduction of indoor temperature, each giving energy savings of respectively 22% and 14%. The upgrading of the U-value of the building envelope and windows could provide an annual energy saving of about 7% each. These results are average values for Sweden, which means that before policy or investment decisions are taken at any other organisational level than the national, the results should be examined in greater detail. The outcomes could also be scrutinised for each climatic region and for different types of buildings; discussions on these topics are outside the scope of this thesis.
- Three scenarios were analysed, which differed with respect to future energy prices.
- The most profitable measures (negative costs) identified are the same in all three scenarios: (1) reduction by 50% of electricity for lighting and appliances; (2) reduction of the indoor temperature to 20°C; and (3) heat recovery measures for single family dwellings. In contrast, the modelling shows that replacement of hydro-pumps with more efficient ones and the retrofitting of all the parts of the building envelope (i.e., attics, basements, and facades) are the most expensive forms of ESM.
- The three scenarios entail similar average annual costs for ESM for the period 2010-2050. This in spite of that the energy price increases up to 0.7% annually in the mitigation scenarios.
- 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. Rather, the profit gained from energy efficiency measures and indirect effects, such as reduced electricity dependency (which may give indirect reductions in CO_2 emissions), are motives for implementing the energy-saving measures.
- Although the application of the ESM would generally reduce CO_2 emissions, the measures that would reduce electricity use for lighting and appliances would increase CO_2 emissions because the saved electricity production is less CO_2-intensive than the fuel mix used for space heating. Therefore, it is not recommended to take decisions based solely on the energy or CO_2 assessment.

At the same time, one should look at the implications of the EMS in terms of delivered energy for the entire energy system.

- The methodology developed in this thesis should be applicable to other countries, provided that the characteristics of the energy performance of the buildings are similar to those in Sweden.

8 Prospects for further studies

Although the modelling system developed during the work of the thesis was validated, further studies are needed to appreciate fully the possibilities for energy-saving and CO_2-mitigation strategies in the building sector.

Even though the work presented in this thesis provides an overall view of the effects of applying a number of energy saving measures (ESM) to existing residential buildings in Sweden, more work is required to identify the optimal approach to implementing these measures. Since the *aggregated* results from applying several ESM, this approach will likely depend on the order in which the ESM are applied. In this thesis, the application of ESM is dictated by increased annual costs. Alternative groupings of the measures, based on technical or operational considerations, are also possible. For instance, it may be reasonable to replace the windows of a building, while at the same time checking the building envelope for air leakages.

It would also be of interest to perform an extended sensitivity analysis with respect to the input data, to determine the relative importance of input parameter variations on the predicted demand outputs.

The work carried out to date does not consider future climate change. Thus, simulations using predicted weather data could be carried out to investigate the effect of a change in climate on the energy usage of an entire building stock. This type of simulation would entail a significant increase in computational time.

One of the priorities is to assess the building stocks of other European countries. Taken together, France, Germany, Italy, Poland, Spain, and UK represent about 70% of the total energy use in European buildings. To analyse the data from these countries, the building physics model may need to be tailored to the characteristics of southern European buildings and non-residential buildings. Most likely, the buildings in these countries need to be represented as *archetypes* defined according to the data available in the literature and statistical sources (see Chapter 3.1), as these datasets are available for most European countries. The first step will be to use Sweden as an example to compare the results of the present work, which is based on sample buildings, with corresponding simulations using archetype buildings.

Another important area for future studies is the incorporation of improvements into the modelling methodology so it can be linked to energy systems models of other sectors of the energy system. In addition, ESM could be assessed with respect to non-technical issues (e.g., consumer behaviour or socio-technical drivers of energy consumption) related to their implementation as the basis for designing policies for stimulating energy savings in buildings.

Finally, demolition and construction dynamics could be included in the modelling. Although the current work focuses on the application of the methodology to Europe, where turnover of the capital stock of buildings is rather low, the inclusion of demolition and construction parameters will be of importance when applying this analysis to estimating long-term changes in energy use in the building sector.

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