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Ex-ante and ex-post modelling of energy performance in buildings

A quantitative analysis of energy use in buildings and how efficiency policy can shape consumption patterns in the Swedish residential sector

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Abstract

Despite energy efficiency is considered as being the most cost-effective measure to reduce energy consumption and carbon emissions in the Swedish residential sector, few barriers still exist that hamper the development of a reliable and effective policy able to shift consumption patterns towards a more sustainable growth.

Although the potential energy savings in the Swedish residential stock are claimed to be high, the few existing quantitative analysis rely on outdated data. In addition, ex-ante evaluations of energy efficiency policies targeting the national residential sector are scarce and often employ general modelling tools, e.g. NORDIC-MARKAL, used to answer any type of energy policy questions. Analysts and policy makers are in clear need of an improved evaluation tool that specifically targets the residential sector and allows for reliable outcomes.

The EEB_Sweden is a flexible modelling tool recently developed to explicitly analyse energy efficiency policies targeting the Swedish residential sector. In this work, the EEB_Sweden platform is further developed by integrating a comprehensive disaggregated set of energy values, associated with current and potential future technological configurations, present in Swedish multi-family buildings. The database is obtained by carrying out energy performance analysis of multi-dwelling buildings belonging to eight different year-of-construction segments and three climate zones, using the sophisticated building energy use simulator eQuest. Once implemented in EEB_Swden, the database is tested by performing some policy scenarios. The outcome is used to assess if energy efficiency policy has the potential to trigger a radical change in the multi-family building segment.

Keywords: Energy Modelling, Policy Evaluation, Swedish Residential Sector

Executive Summary

This thesis addresses an existing energy-efficiency gap between actual and optimal energy consumption in the Swedish residential sector. Despite cost-effective technologies can help reaching an optimal level and reduce the gap, the diffusion process is still very slow. Only by identifying existing barriers limiting energy efficiency it will be possible to introduce ad hoc policy measures aiming for a more sustainable growth of the residential stock.

Ex-post and ex-ante evaluations of energy efficiency policies are necessary to understand the effect of instruments already implemented and assess the outcome of future measures. Their role is crucial for analysts and policy makers intending to develop improved and effective energy and environmental policies. However, these analyses have been scarcely conducted for the Swedish residential sector. Furthermore, the few existing are based on old data, collected in the decade between 1983 and 1993, and are therefore not reliable anymore. In addition, ex-ante policy analysis is generally carried out using general modelling tools, such as MARKAL-NORDIC, suited for all kind of energy policy evaluations. For this reason, projected scenarios are very often not realistic and experts are increasingly questioning the capability of conventional energy and economic models to adequately represent technology and policy measures.

In order to address these issues, flexible modelling tools are being developed, which are able to also incorporate non-technological-economic parameters (e.g. indoor environmental quality, technology ease of use and installation, and appearance) and to target a specific sector. The EEB model is an example. It was developed for a project on Energy Efficiency in Buildings, sponsored by the World Business Council for Sustainable Development (WBSCD), to explicitly analyse energy efficiency policies targeting the building sector. Mundaca and Neij (2010a) have developed the EEB_Sweden simulation tool to quantitatively represent the Swedish residential sector, and to generate and evaluate energy efficiency policy scenarios.

However, EEB_Sweden still lacks a detailed technology and energy database for the Swedish residential sector, critical for the full development of the platform. This set of data would allow for more reliable results and help to better evaluate the outcomes. The creation of such database represents the core of this study.

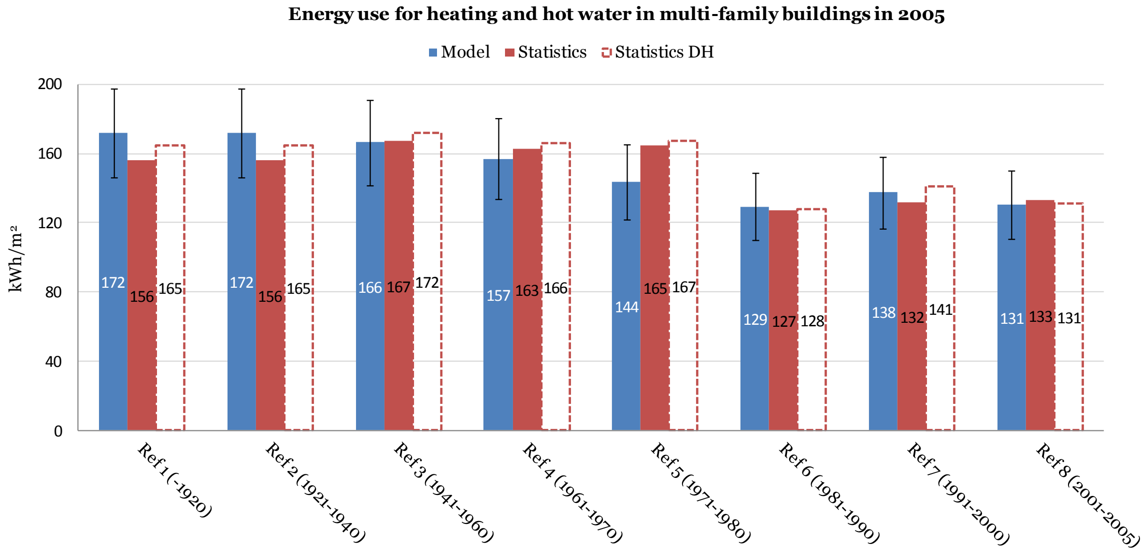
First phase of this work consisted in gaining an understanding of the Swedish multi-family residential sector. Information about residential facts, architectural features, mechanical parameters, electrical features, internal loads, and environmental aspects was collected and investigated.

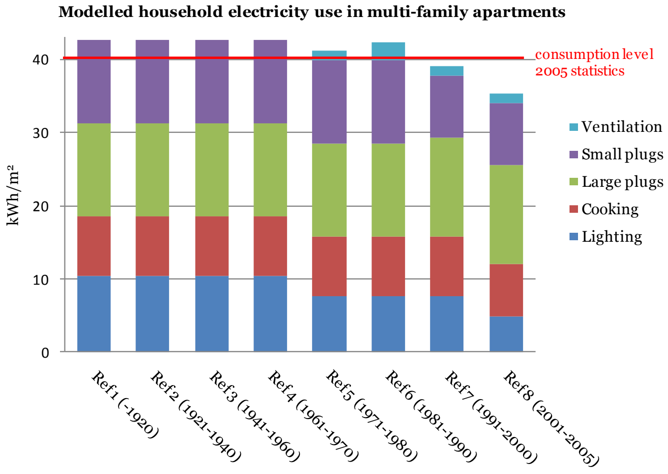
Building energy performance analyses were carried out with eQuest, which is considered as one of the most sophisticated building energy use simulators on the market. eQuest allowed to estimate disaggregated energy values associated with current and potential future technological configurations in the Swedish multi-family residential sector. For this purpose, 24 building models were created, reflecting eight year-of-construction segments, and three climate zone.

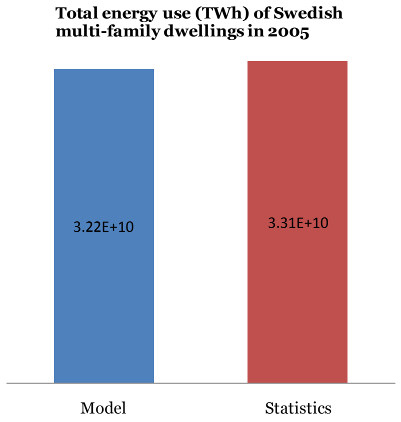
Baseline models are united by the following features, extrapolated from the definition of average multi-family building in the recent BETSI project (Boverket, 2010): buildings consists of three floors and a cellar; the total heated area is 1426 m^2, including apartments and common areas, such as laundry room, corridors and storage rooms. In the building there are 15 apartments, each of them with an area of 68 m^2 and with 2 occupants. Heating and domestic hot water is provided by DH. On the other hand, elements such as envelope insulation, fenestration and ventilation equipment differ according to the building year of construction. In addition, consumption patterns strongly depend on geographical location.

The outcome was a set of specific energy values for space heating and space cooling equipment, ventilation equipment and distribution, lighting and cooking equipment, water heating system, large and small plug devices. During and after the analysis process, modelled values were benchmarked and compared with statistical data from by the Swedish Energy Agency, Statistics Sweden and the Swedish National Board of Housing, Building and Planning. Sensitivity analyses were also carried out to ensure the reliability of modelled values within a reasonable range of error.

The main outcomes of the analysis with eQuest are reported in the next figures and can be summarised as follows: modelled energy consumption for district heating and domestic hot water differs from statistics within the default ± 15% margin of error to be attributed to results obtained with eQuest. Electricity consumption in households is on average slightly higher than statistical values. Estimated and official total energy consumption for the multi-family segment can be considered equal within a 3% range of uncertainty.







Moreover, sensitivity analyses identified only negligible deviations from baseline values. Besides providing estimates of the energy performance of the multi-family stock in 2005, energy values attributed to several technology packages reflecting future permutations in buildings were also calculated. For this purpose, baseline models were implemented, for instance, with improved envelope insulation and windows, more efficient heating systems, lighting control devices and thermostats.

The created multi-family energy performance database was included in the EEB_Sweden platform. Then, two baseline and four test policy scenarios were simulated with the implemented version of the EEB_Sweden model, in order to comprehend, ex-ante, how future patterns in energy consumption in buildings is affected by specific measures that could be adopted by policy makers.

As baseline scenarios, market response and current Swedish energy policy were chosen. The former reflects the case where no policy instruments are introduced and energy prices are kept the same as in 2005. The latter intends to incorporate the economic instruments adopted by the Swedish government for improving energy efficiency in the residential sector, in year 2005. In specific they are: building regulations, 65% reduction in the investment cost for implementing solar PV and 35% cost reduction for converting the heating system. In both cases, the simulated per building energy consumption in 2050, with respect to 2005, decreases. Compared to the business-as-usual case, current policy seems to achieve only a slight improvement in the multi-family stock (-2% on per-building energy use), and is still far from attaining a radical change in consumption and in carbon emission patterns in the residential sector.

Additional four policy scenarios were simulated: (i) zero net energy building (ZNEB), (ii) 10x raise in energy prices, (iii) financial incentives and (iv) carbon tax, bans & incentives.

With the database developed in this work, the ZNEB case is not feasible: on-site energy generation from solar thermal and solar PV is not enough to balance out consumption in buildings. This is in disagreement with the EEB analysis on single and semi-detached houses performed by Mundaca and Neij (2011), where average EU-15 data was used to picture the Swedish residential sector, stressing the importance of using a tailor-made database for the specific country under analysis.

In the second scenario, an energy price increase is introduced gradually to reach a factor 10 in 2050. No net increase/decrease in per-building energy use is observed, most likely depicting a situation were decision-makers tend to avoid capital expenses for efficiency improvements in a time of pressing energy price increase.

In the case of financial incentives, economic grants, in form of capital and labour cost reduction, are given when constructing new buildings that have a yearly energy consumption equal or below 90 kWh/m^2. The simulation outcome suggests that the incentive measures are responsible for lowering the energy consumption in buildings by 3% at the end of the 45 years of analysis.

Finally, the fourth scenario introduces a 30$ carbon tax per metric ton of CO_2 emitted, financial incentives for energy-efficient new buildings (as in scenario 3) and a ban for refurbishing buildings with yearly energy consumption above 230 kWh/m^2. The outcome is a critical decrease in energy consumption, thus proving that more integrated policy instruments have the potential to trigger a radical transformation in the multi-family sector.

Results from policy simulations can be summarised in the following table:

	Primary energy use variation		Building energy use variation	
2050/2005	Simulation results	Without baseline	Simulation results	Without baseline
(b1) Market response	+380%		-6%	
(b2) Current Swedish energy policy	+357%		-8%	
(s1) 10x raise in energy prices + b2	+356%	+1%	-8%	±0%
(s3) Financial incentives + b2	+337%	-20%	-11%	-3%
(s4) Carbon tax, bans and incentives + b2	+231%	-126%	-27%	-19%

Last, it is important to highlight that the EEB_Sweden model is still under development and the simulation exercise aims to feedback and improve the development of the model as such. The estimation of current energy performance is critical to calibrate the model and reduce uncertainty of estimated future values. In all, quantitative estimates must be taken with due caution.

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Abbreviations

A_{temp}	Heated area
A_{walls}	External walls' area
$A_{windows}$	Windows' area
CFL	Compact Fluorescent Light
DH	District heating
DHW	Domestic Hot Water
E3	Energy-Economy-Environment
EEB	Energy Efficiency in Buildings
GHG	Greenhouse gas
HVAC	Heating, Ventilation and Air Conditioning
kWh	Kilowatt hour
kWh/m^2	Kilowatt hour per square metre
MWh	Megawatt hour
NZEB	Net Zero Energy Buildings
Ref	Reference year-of-construction segment
SEPA	Swedish Environmental Protection Agency
TWh	Terawatt hour
U	u-value
WBCSD	The World Business Council for Sustainable Development

1 Introduction

1.1 Research background

Raising global problems of energy security, resource scarcity and global warming have accelerated the urge for a consistent strategy that highlights a responsible production and use of energy. However, despite the pressing need to conserve and use energy efficiently, supply and demand patterns remain unsustainable.

Our society is heavily dependent on fossil fuels. Since these resources are limited and confined to a few areas on our planet, the supply flow is steered by economical and political aspects. Although their depletion cannot be predicted with certainty, scarcity effects have already materialised into increased fuel prices and political instability. (NATO, 2008) In addition to insecurity the growth and the demand for welfare, especially by developing countries, will cause the global energy demand to raise by 40% between 2009 and 2035 (IEA, 2011). This has triggered an exponential increase in energy production and a true hunt for today's gold: energy resources. Furthermore, the environmental impact linked to energy production, as resource depletion and global warming due to greenhouse gas emissions, is unquestionable. In this scenario, concrete energy conservation and energy efficiency measures are a priority that cannot be disregarded any longer.

Energy efficiency is a crucial means of saving energy. According to the second law of thermodynamics, when matter is transformed from one state to another, loss of energy in form of heat occurs. The useful work obtained from the most commonly used energy sources is only a tiny fraction of the original energy content of the primary component. Data from the International Energy Agency (2009c) shows that the average net output from electricity generation for primary energy sources in the world is only 33%. Aside from the degradation of energy quality imposed by the laws of physics, energy is wasted unnecessarily mainly due to inefficient equipment (e.g. industrial motors, coal and nuclear power plants, vehicles and incandescent light bulbs) (Miller, 2009). A clean and effective way to increase energy service[1] provision along with decreased pollution and environmental degradation is the reduction of this waste. This goal is still far from being achieved: beside technological limitations, market and behavioural failures, ineffective or absence of policies have been identified as the main causes (Johansson, 2006; Mundaca, Neij, Worrell, & McNeil, 2010).

These factors have been subject of debate in the overall study regarding the *energy-efficiency gap*, defined as the existing gap between actual and optimal energy consumption, both present and future. In their work, Jaffe and Stavins (1994) assert that the gap extent depends on "*how optimal behaviour is defined*"; in fact, the level of optimality can be described from different perspectives, e.g. by economists, technologists or social scientists, as also pointed out by Sanstad and Howarth (1994). Each of them gives their explanation to one basic question: if cost-effective energy-efficient technologies exist, why are they not widely used? Only by analysing existing market barriers and failures will it be possible to introduce more innovative, ad hoc policy actions that will help enhancing the availability of information and accelerating the diffusion process of energy-efficient technologies. (Jaffe & Stavins, 1994)

In this scenario, ex-ante policy analysis plays a crucial role: the ability to evaluate policy instruments and foresee their outcome before their implementation is of obvious major

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[1] According to the definition provided by GEA (2012) energy services "*refer to illumination, information and communication, transport and mobility of people and goods, hot water, thermal comfort, cooking, refrigeration, and mechanical power*". Therefore, energy carriers such as electricity and gas are not energy services.

interest for policy makers. This assessment process usually occurs through modelling tools. Specifically, bottom-up energy-economy-environment (E3) models help create energy efficiency scenarios and evaluate policy instruments by considering technological features, performance and costs to obtain economic and environmental impacts (Mundaca & Neij, 2010b; Nakata, 2004). Despite their extensive use, their accuracy and reliability have been discussed, taking into account the increased complexity of energy systems, environmental problems and technological developments. (Fiddaman, 2002; Hourcade, Jaccard, Bataille, & Ghersi, 2006; Mundaca & Neij, 2011; Mundaca, et al., 2010)

In fact, E3 models are considered to be very general and developed for a broad use, independently from the sector to be analysed. Models with a bottom-up approach are able to estimate in detail the current and future degree of competitiveness of energy technologies, both on the supply- and demand-side, and relate them to different environmental impacts. However, models have been criticized for not offering a realistic view of micro-economic decision-making by consumers when choosing technologies (Hourcade, et al., 2006). In fact, in the most commonly employed platforms, user behaviour and practice are neglected. Consumers or companies are modelled as individuals that know everything of energy-efficient technologies; their decisions are modelled as homogeneous and merely relying on energy-related or economic factors. In reality, decisions are also influenced by parameters like design, comfort, brand, functionality, reliability and environmental awareness. (Neij, Mundaca, & Moukhametshina, 2009) Therefore, the projected scenarios are very often not realistic, resulting in a clear mismatch between ex-ante and ex-post policy assessment.

1.1.1 Research problem

In a society facing significant global issues such as environmental degradation, increased energy demand and resource scarcity, the need for innovative and effective policy instruments is urgent. Therefore, improved policy evaluation tools that result in better energy and environmental policies are clearly a necessity.

Lately, particular attention has been addressed to the residential sector's energy demand and potential savings due to efficiency measures. Although the stock accounts for only 19% of the world's total energy consumption today, projections show that its electricity demand will rise by 88% between 2009 and 2035 primarily due to an increase in population, increased access to the grid and increased use of modern electrical appliances (IEA, 2011). Carbon emissions attributed to the building sector (including electricity use) will increase from 8.2 $GtCO_2$ registered in 2004 to 11.4-15.6 $GtCO_2$ predicted for 2030, representing approximately 30% of the total carbon emissions (IPCC, 2007). Efficient technologies and practices, if implemented in old and new buildings, could help in saving 34% of the estimated building primary energy use by 2020. Such a radical change would allow, by 2030, a reduction in energy use in buildings equal to the actual total energy consumption in Europe. (UNFoundation, 2007)

In the EU, the residential sector demands on average 28% of the total energy consumption. In the last ten years, the European Council has engaged in several actions with the specific aim of affecting energy generation, distribution and usage. The EU Directive Concerning the Energy Performance of Buildings (2002/91/EC) adopted in 2002 is an example (European Parliament, 2002). It aims to improve the energy efficiency in the built environment, reduce the importation of energy and lower greenhouse gas emissions. More specifically, in order to reduce energy inefficiencies, in 2006 the European Council called for tangible measures and adopted the Action Plan for Energy Efficiency (EU, 2006) that would help realising the challenging goal of reducing primary energy consumption by 20% in 2020. In the document, a series of policies and measures are described with the aim to push for immediate actions: innovation and technology, energy performance requirements, financing tools and economic incentives, increased individual awareness and behavioural change are key wordings in this call. If adopted appropriately, the European Commission has estimated that these actions have the potential to save up to 27% of the energy consumed in the residential sector by 2020. (EU, 2006) According to a more recent study performed by the Fraunhofer Institute (2009) on behalf of the EU, a less optimistic scenario is described where only a 19% of energy gains in respect to the business-as-usual baseline are expected if additional policy measures are implemented. Additionally, this year, Mills and Schleich (2012) report that the EU energy efficiency target is likely to be missed if no additional actions are taken.

Besides the need for action at the EU level, it is of crucial importance that differentiated actions are taken at the member state level, since households' characteristics, technology choice and energy conservation habits varies from country to country. (Mills & Schleich, 2012)

In Sweden, 23% of the total energy consumption is attributed to households. Although energy efficiency has been addressed as being the most cost-effective measure to secure energy supply and reduce carbon emissions, there are still a few barriers that limit the achievement of such target in Sweden.

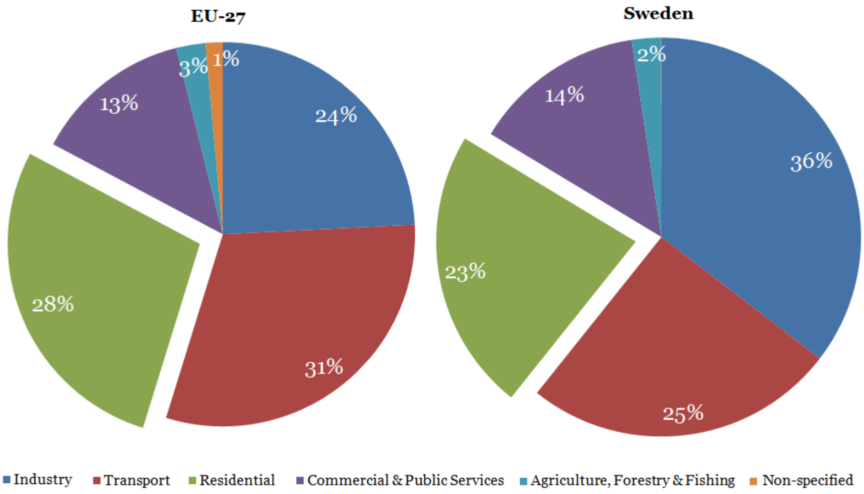

Figure 1- 1: Share of energy consumption by sector, in EU-27 and Sweden in 2009.

Source: (IEA, 2009a, 2009b)

First of all, the quantification of the efficiency potential is no longer trustworthy: only a few studies have been performed to understand to which extent energy can be saved in the Swedish residential sector, e.g. in 1996 by the Swedish Institute for Building Research (Byggforskningsrådet, 1996) and in 2005 by the EnergiCenter department at Chalmers University (CEC, 2005). Additionally, most of these works are based on old data, retrieved from research projects conducted more than 20 years ago: for example, ERBOL (Boverket, 2010) was a project performed by the Swedish Institute for Building Research in 1983-84 targeting the residential and commercial buildings. The outcome of this analysis was a series of suggested technical measures that could help saving energy in households and premises. The study ELIB (Borgström, 1993; Engebeck, 1993), completed in 1993, analysed the building stock technical characteristics, energy use and indoor climate. In 1994, a project run by Nutek (1994) focused on technology improvements that could be achieved by installing more efficient appliances.

Consequently, driven by a strong need for new data, the government appointed the Swedish National Board of Housing, Building and Planning to develop an updated description of the Swedish building stock; the project, called BETSI and finalised in 2010 (Boverket, 2010), consisted in obtaining through nationwide surveys, buildings' energy use, technical status and indoor environment. This new database will most likely trigger new evaluation studies of energy efficiency potential in the residential sector, as already seen in the work by Mata et al. (2010), which quantifies technical potential savings equal to 56 TWh/yr, corresponding to 58% of the yearly baseline consumption of the sector.

Another consistent barrier is the lack of policy evaluation studies. Especially in the last ten years, policy makers have adopted several actions to target energy inefficiencies (Johansson, 2006). For instance, as a response to the EU target of a 20% reduction in energy consumption by 2020, for all new or fully-renovated buildings, Swedish government has set mandatory energy consumption calculation methods and has imposed a minimum performance obligation. (Johansson, 2006) Recently these technical requirements were strengthened by the Swedish National Board of Housing, Building and Planning (Boverket). Moreover, in 2008 the Swedish government introduced a financial support (ROT reduction) for individuals aiming for renovation or maintenance; moreover, financial aid was also provided for installing solar PV and solar thermal (the programme ended in 2011). These actions aim at reducing energy use in the residential sector and increase the share of renewables in the national energy mix. (Energimyndigheten, 2011b)

Despite the numerous actions, the "[...] *evaluations of policy instruments in respect to their effects on energy efficiency have merely been scarcely performed in Sweden*" as the Swedish Energy agency (2009) reported in one of its last reports. Analysing policy actions ex-post is evidently useful; however, being able to assess the outcome of these instruments before (ex-ante) implementing them is even more valuable. Unfortunately, only a few ex-ante policy evaluation studies have been carried out for the Swedish residential sector (Mundaca, 2008). On the contrary, analyses on the effects of carbon emissions in relation to climate mitigation strategies are more common (SEA, 2009). For example, the Nordic Energy Perspectives (Ryden, 2006) was a research project with the aim to evaluate energy policy instruments (in Nordic countries) and their influence on energy markets and energy systems. Six different modelling tools were used in this analysis, including MARKAL-NORDIC, i.e. a Nordic version of the comprehensive bottom-up model generator MARKAL[2], widely used for policy analysis in Sweden and not addressing qualitative aspects of energy efficient technology choice. More recently, the Swedish Energy Agency (2012) was appointed by EU to investigate the consequences of a more ambitious emission target reduction, i.e. 30% instead of 20%, by 2020. The analysis was performed once more with MARKAL-NORDIC.

Neglecting non-financial parameters for technology choice into models unequivocally brings to discrepancies between created scenarios and real future trends. Policy makers and analysts are increasingly questioning the capability of conventional energy and economic models to adequately represent technology and policy measures (Laitner & Hanson, 2006). Moreover, policy makers seem to be frustrated because the same modelling tools (e.g. MARKAL) are used to answer any type of energy policy questions - not only in the field of energy efficiency. Furthermore, the present ex-ante evaluation tools are able to analyse only a limited portfolio of policy instruments and neglect more innovative or ambitious measures such as maximum energy performance thresholds and net zero energy buildings (Mundaca, 2012).

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[2] MARKet ALlocation (MARKAL) is an engineering-economic linear programming tool for energy system analysis. (Mundaca, et al., 2010)

In order to address this problem, flexible modelling tools are being developed, which are able to also incorporate non-technological-economic parameters and to target a specific sector. An example is the comprehensive EEB model, developed for a project about Energy Efficiency in Buildings, and sponsored by the World Business Council for Sustainable Development (WBSCD), to explicitly analyse energy efficiency policies targeting the building sector. Most important, EEB gives the opportunity to integrate non-financial criteria affecting technology choice (Mundaca & Neij, 2010a). Mundaca and Neij (2010a) have developed the EEB_Sweden_v1.0 simulation tool to quantitatively represent the Swedish residential sector, and to generate and evaluate energy efficiency policy scenarios, taking into account also non-financial criteria.

However, the developed model still lacks a detailed technology and energy database for the Swedish residential sector. The development of such an energy performance database is critical for the full development of the EEB_Sweden v 1.0 model. In fact, incorporating detailed information of energy values associated with different technological configurations in Swedish households into the EEB_Sweden model allows obtainment of more reliable results and better evaluation of outcomes. The database would facilitate the development of the EEB_Sweden model, turning it into a tailor-made tool for evaluating energy efficiency policies targeting the Swedish multi-family stock.

1.2 Purpose, objective and research questions

Based on the above, the overall purpose of this study is to increase our knowledge about energy performance, energy efficiency potentials, and the role of policy instruments as applied to the Swedish residential sector. The objective of the research is to carry out an energy performance analysis of the Swedish multi-family residential sector and create an extensive energy database to further develop the EEB_Sweden modelling platform. The implemented database is crucial to better analyse the potential impact of different policy instruments in the Swedish residential sector.

For this specific objective, building energy performance analyses were carried out in order to estimate the energy values associated with current and potential future technological configurations in the Swedish multi-family residential sector. This quantification process, representing the core of this work, enabled to associate an energy value to each main technology present in Swedish multi-family dwellings, and can be considered unique in its kind. The created multi-family energy performance database was included in the EEB_Sweden platform, and test policy scenarios were simulated to comprehend the transformation potential of these measures and compare the results with similar studies.

To that end, the research at hand is guided by the following research questions:

- What are the current technology configurations and corresponding energy values of the Swedish multi-family residential sector?

- What is the current disaggregated energy performance of the Swedish multi-family building stock?

- What is the potential for policy to increase energy efficiency and encourage radical transformation in the multi-family building segment?

1.3 Scope and limitations

This study aims to perform an energy policy evaluation of the residential sector in Sweden considering 2005 as the reference year. In particular, the analysis is carried out on multi-family dwellings, excluding single and two-family houses. Moreover, the building performance analysis is based on Boverket's definition of average multi-family building (2010), considering as modelling energy variables the technology configuration, building construction year, and climatic features. Estimated values were calibrated and benchmarked with energy data retrieved from Statistics Sweden and the Swedish Energy Agency (SCB/Energymyndigheten, 2006).

Eight technology groups were chosen and incorporated in the performance analysis since they represent the main input categories in the modelling tool used for energy performance analysis (eQuest). They are: fenestration, walls insulation, roof insulation, space heating equipment, space cooling equipment & distribution, ventilation equipment, water heating equipment and home appliances. Building elements such as overhangs, fins, window blinds and rooftop skylights were not taken into account in the modelling process.

Climate affects energy consumption in households. Therefore, weather conditions have to be incorporated into the performance analysis. Sweden can be divided into three climate zones (Boverket, 2009). In the analysis, weather data from one representative city within the region boundaries was attributed to the whole area. Weather data was gathered from Kiruna, Karlstad, and Gothenburg.

Finally, it is important to highlight that the EEB_Sweden model is still under development and the simulation exercise contained in this thesis aims to feedback and improve the development of the model as such. The estimation of current energy performance is critical to calibrate the model and reduce uncertainty of estimated future values. In all, quantitative estimates must be taken with due caution.

1.4 Content

The outline of the thesis is as follows. Chapter 2 gives a thorough description of the methodology employed for this research project. In particular, information on the data acquisition process, along with statistical figures, is provided in the first section. Chapter 2 also reports how the analysis process was carried out, explaining in detail the tool for energy performance calculations, eQuest, and the platform for policy scenario modelling, EEB. The simulation process is described step-wise and main assumptions are illustrated.

In Chapter 3, major results are reported. In the first part, the outcome of the energy performance analysis for the current multi-family building stock is illustrated and compared to statistical values. Moreover, potential energy gains obtained by implementing new technology packages are shown. Finally, deviations from baseline models are explained through a sensitivity analysis on weather factors and building features. In the second part, policy scenario simulations are reported and examined.

Chapter 4 aims to describe the highlights of this work and discuss future trends.

2 Methodology

This study was carried out step-wise by first performing a literature review, then collecting data and finally making the energy performance and policy analysis.

Various literature sources were investigated, including academic papers, reviews and online information on energy efficiency and the built environment, energy modelling and policy. This allowed to deepen the understanding of the field, to recognise the main challenges and limitations of energy-efficiency-related issues and to identify the tools needed to improve the current situation.

2.1 Methods for data collection

Data collection was performed by scrutinizing articles, reports and statistics published by the Swedish Energy Agency (Energimyndigheten), Statistics Sweden (Statistiska Centralbyrån), the Swedish National Board of Housing, Building and Planning (Boverket), the Swedish EPA (Naturvårdsverket) and other databases at the EU level (Mure-Odyssee, Tabula). Moreover, several academic papers, dissertation and technical reports were considered in order to fill the gaps left by the above mentioned sources. An essential role was played by the reports published by Mundaca et al. (2010a, 2011), which allowed to gain an overview of the available residential building stock data and of the most relevant energy consumption influencing factors, as well as an insight on the EEB_Sweden v1.0, developed by the same authors.

Next sections intend to describe the data collection process and the reasoning behind it. Also, they aim to illustrate the Swedish multi-dwelling residential sector by showing key elements and values needed for the analysis phase.

2.1.1 Multi-family buildings input data

Target of the investigation were data regarding multi-family dwellings in Sweden, such as residential facts (e.g. number of multi-family buildings and apartments according to the year of construction, location in relation to the climate zones), architectural features (e.g. building and zone areas, number of floors per building, construction technique and materials, surface areas), mechanical parameters (e.g. heating and cooling systems), electrical features (lightning equipment), internal loads (peak occupancy, lightning and equipment, water usage), commercial prices (e.g. energy, material and technology) and environmental aspects (i.e. CO_2 emission factors).

Table 2-1 aggregates the data needed in order to develop the energy performance models with the software eQuest (§2.2.1), and further for the policy scenario evaluation using the EEB_Sweden tool (§2.2.2). In particular, the table indicates the type of data, the items, the specific values and the sources where they were collected from.

In Sweden, multi-family buildings are mainly apartment buildings and semi-detached houses, respectively 41% and 25% of the total stock (Boverket, 2010). In this work, buildings are divided in eight segments reflecting their year of construction. For simplicity, these segments are indicated with the abbreviation Ref 1 to Ref 8 and represents the following time ranges: Ref 1 until 1920; Ref 2 1921-40, Ref 3 41-60, Ref 4 61-70, Ref 5 71-80, Ref 6 81-90, Ref 7 91-2000, and Ref 8 2001-2005.

Each reference segment is characterised by specific technologies and construction materials. In this study, eight categories are taken into consideration for modelling purposes, in agreement with the input classes in eQuest: fenestration, wall insulation, roof insulation, space heating equipment, space cooling equipment and distribution, ventilation, water heating equipment, indoor household appliances.

Table 2-2 lists these types of technology and construction materials with corresponding u-values. In the table, the term U stands for u-value, or heat transfer coefficient[3], and indicates how a specific building element conducts heat, hence, how well isolated it is. Home appliances adopted for each reference segment are listed in Table 2-5.

Consequence of diverse technology use and insulation properties of buildings belonging to different reference segments is a differentiated energy use for heating and warm water, as shown in Figure 2-1. Electricity use for household purpose is considered constant for all dwellings and is equal to 40 kWh/m^2, as indicated in table 2-1(Energimyndigheten, 2005).

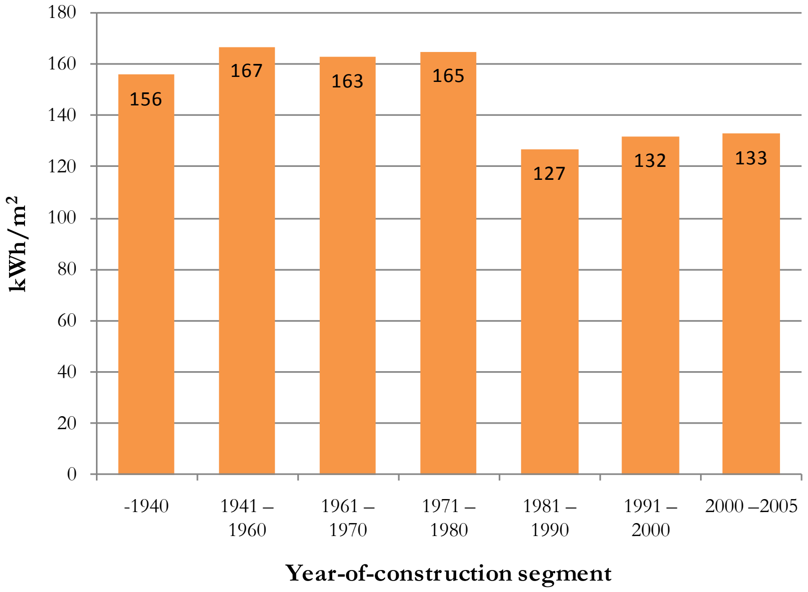

Figure 2- 1: Average energy consumption for heat and hot water according to the year of construction. Reference year 2005.

Source: (SCB/Energymyndigheten, 2006)

2.1.2 Variables and influencing parameters

Since the very beginning, it was clear that one single model for each year-of-construction segment was not enough in order to represent the energy performance of multi-family buildings in Sweden. In fact, although it is possible to define an average usage in terms of HVAC (heating, ventilation and air conditioning) systems, electrical features and internal loads that holds true for the entire country, building location and architectural features differ sensibly and can radically affect energy consumption.

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[3] The overall heat transfer coefficient U measures the ability of conductive and convective materials to transfer heat over a given area at 24 °C, 50% humidity and with no wind. The smaller is the U-value, the better is the isolation. It is measured in W/m^{2}K.

Table 2- 1: Data needed for energy performance modelling with eQuest and policy scenario analysis with EEB_Sweden, divided in categories, items, values and sources.

Sources: included in the table

Category	Item	Value (2005)	Source
Residential	Number of multi-family buildings and dwellings in Sweden	165 000; 2 396 962	(Boverket, 2010; SCB, 2012a)
	Number of multi-family dwellings for each climate zone and year-of-construction segment	See separate Table 2-3	
	Avg number of dwellings per building	14.55	
	Avg number of occupants per dwelling	1.7	
	Avg area per flat (m²)	68	
	New building growth rate and building demolition rate	3.2%; 0.07%	
Energy	Total energy use (TWh)	33.07	(Energimyndigheten, 2012b)
	Avg energy use for household purpose (kWh/m²)	40	(Energimyndigheten, 2005)
	Avg energy use for heat and hot water (kWh/m²)	162	(Energimyndigheten, 2005)
	Avg energy consumption for heat and hot water per year-of-construction segment	See Figure 2-1	(SCB/Energymyndigheten, 2006)
Architectural	Building type	Apartment building, semi-detached	(Boverket, 2010)
	Envelope construction materials or u-values	See separate Table 2-2	(Boverket, 2010; IntelligentEnergyEurope, 2012)
	Heated surface area (m²)	238 000 000 (162 928 000 excl. common areas)	(Boverket, 2010)
	Fenestration areas (10^6 m²), orientation and u-values	6.2 (North), 7.5 (South), 8.4 (West), 7.7 (East) For u-values see separate Table 2-2	(Boverket, 2010)
Mechanical	HVAC equipment description	See separate Table 2-2	See separate Table 2-2
Internal loads	Peak occupancy, lightning and equipment	Typical use; occupancy weekdays: 4pm-8pm, occupancy weekends/public holidays: 3pm-10am.	Assumption
	Avg warm water consumption/person (l/day)	76	(Ek & Nilsson, 2011)
	Indoor temperature (°C)	22	(Boverket, 2010)
Economy	Energy cost	See separate Table 2-4	See separate Table 2-4
Environment	Emission factors	See separate Table 2-5	See separate Table 2-5

Table 2- 2: Technology configuration and corresponding u-values for multi-family buildings in Sweden, divided by category and year-of-construction segment. Sources are indicated in the right-most column. Adapted from: (Mundaca, 2012; Mundaca & Neij, 2010a).

Sources: included in the table.

Technology/ Material	**Ref 1 -1920** [U]=W/m²K	**Ref 2 1921-1940** [U]=W/m²K	**Ref 3 1941-1960** [U]=W/m²K	**Ref 4 1961-1970** [U]=W/m²K	**Ref 5 1971-1980** [U]=W/m²K	**Ref 6 1981-1990** [U]=W/m²K	**Ref 7 1991-2000** [U]=W/m²K	**Ref 8 2001-2005** [U]=W/m²K	**Source**
Fenestration	1+1 coupled-glazed U=3.0	1+1 coupled-glazed U=3.0	Double pane U=2.25	Double pane U=2.25	Triple pane U=2.00	Triple pane U=1.80	Double pane U=2.00	Triple pane U=1.80	(Boverket, 2010)
Walls insulation	U=0.58	U=0.58	U=0.58	U=0.41	U=0.33	U=0.22	U=0.20	U=0.20	(Boverket, 2010)
Roof insulation	U=0.36	U=0.36	U=0.36	U=0.20	U=0.17	U=0.17	U=0.15	U=0.13	(Boverket, 2010)
Floor insulation	U=0.36	U=0.36	U=0.36	U=0.32	U=0.28	U=0.26	U=0.24	U=0.22	(IntelligentEnergyEurope, 2012)
Space heating equipment	DH η=0.85	DH η=0.85	DH η=0.85	DH η=0.85	DH η=0.85	DH η=0.85	DH η=0.85	DH η=0.85	(Boverket, 2010; IntelligentEnergyEurope, 2012)
Space cooling equipment	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Assumption
Ventilation	Natural	Natural	Natural	Natural	Mechanical exhaust	Mechanical supply+exhaust w air recovery	Mechanical exhaust	Mechanical exhaust	(Boverket, 2010)
Water heating	DH w tank	DH w tank	DH w tank	DH w tank	DH w tank	DH w tank	DH w tank	DH w tank	(Boverket, 2010)

Despite Table 2-2 gives an accurate sub-division of technology types and material categories, incorporated in the u-values of the envelope building materials, some features are still important variables and need to be taken into account in the modelling process; in particular, climate, building size and building technique. For instance, a two-floors building without underground space in Kiruna will intuitively have a different energy performance than a four-floors building with cellar in Malmö.

However, considering the wide variety of multi-family building types, in order not to unnecessarily enlarge the modelling scenario, a balance between accuracy and number of models has to be found. Therefore, when a certain feature prevails, that element is used for modelling all buildings, while the other types are neglected. In this work, a specific building feature is considered to be prevailing when it is included in more than 50% of the total number of buildings in consideration.

As a consequence, during the data collection process, a first selection of prevailing features was performed. During the data analysis, these elements underwent an additional filtration in order to select only the relevant parameters that could sensibly affect the energy performance.

An illustration of this process is given in Figures 2-2, 2-3, 2-4 and 2-5.

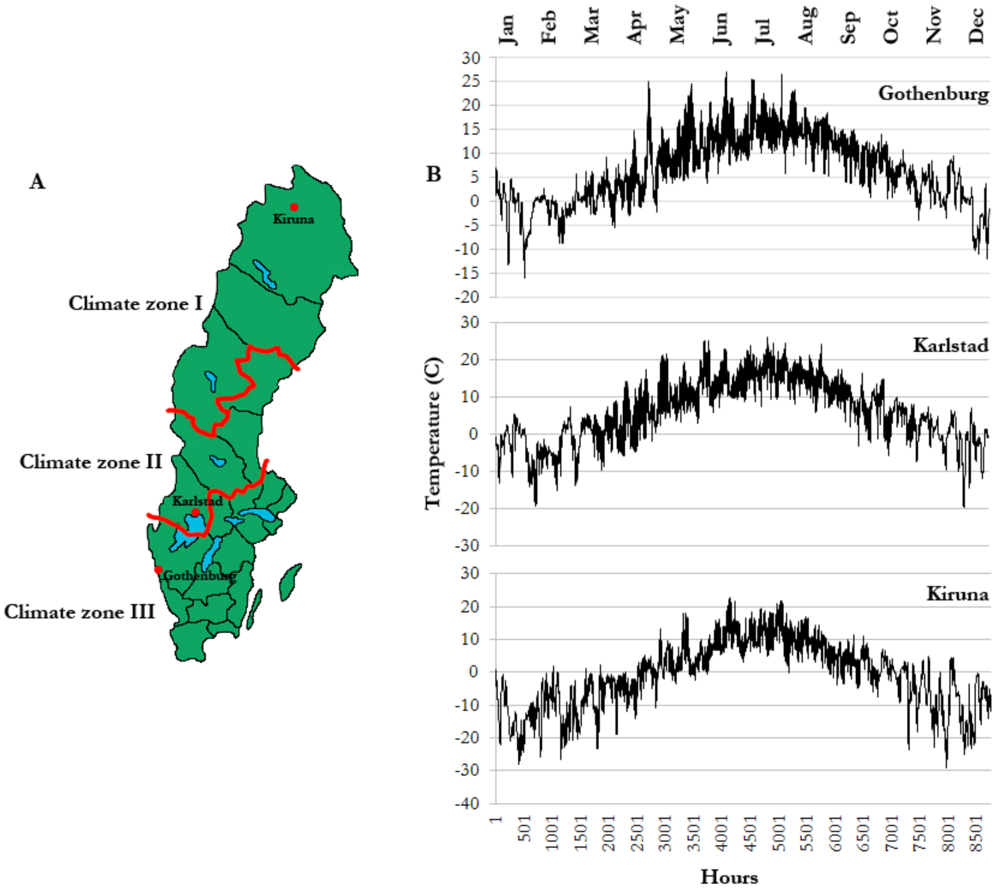

Figure 2- 2: A. Sweden's climate zoning (adapted from www.rockwool.se) with reference cities. B. Yearly temperature values for the cities of Gothenburg, Karlstad and Kiruna, reference year 2001 (Copyright 2001 American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), Inc., Atlanta, GA, USA).

Sources: (DOE2, 2001; Rockwool, 2012)

Figure 2-2A shows how Sweden can be divided in three climate zones (Boverket, 2009). Climate zones have been defined in order to allow for differentiated requirements on buildings' energy use with respect to the temperature of the site. Climate zones are named from north to south, I, II and III respectively. Zone I includes the regions of Norrbotten, Västerbotten and Jämtland; zone II comprises the regions Västernorrland, Gävleborg, Dalarna and Värmland; finally, region III embraces the rest of Sweden, namely the regions Stockholm, Uppsala, Södermanland, Östergötland, Jönköping, Kronoberg, Kalmar, Gotland, Blekinge, Skåne, Halland, Västra Götaland, Örebro and Västmanland.

The climate attributed to buildings located in the same zone refers to the weather data collected from one single city, indicated in panel A. More explicitly, all buildings in climate zone I will be modelled with the weather file of Gothenburg, buildings belonging to climate zone II will be modelled with the weather file of Karlstad and buildings of the climate zone III with the weather file of Kiruna. This assumption is mainly motivated by a lack of data (at present only five weather files from 2001 are available free of charge for Sweden (DOE2, 2001), specifically for the cities of Göteborg, Karlstad, Kiruna, Stockholm and Östersund), and, most important, by the fact that temperature variation amongst cities belonging to the same climate zone can be neglected (see sensitivity analysis results in Chapter 3). Panel B shows a graphic representation of temperature variations (black solid line) for each representative city. Temperature variation is only one element of the weather file that also includes information on humidity, wind and solar radiance.

In order to carry out the energy performance analysis with eQuest, information on how many multi-family dwellings belong to each year-of-construction segment and climate zone is needed. Figure 2-3 illustrates the available statistics (Boverket, 2010; SCB, 2012a).

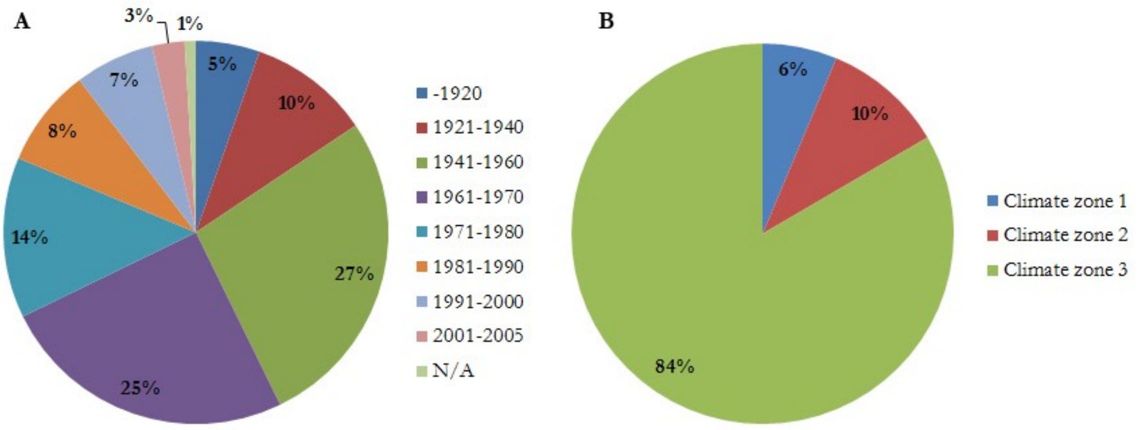

Figure 2- 3: Distribution of Sweden's multi-family dwellings by year-of-construction segment (panel A) and climate zone (panel B). Reference year: 2005.

Sources: (Boverket, 2010; SCB, 2012a)

Table 2-3 lists the number of dwellings belonging to buildings constructed in different time ranges and how these are distributed in the three climate zones. The latter values (the three right-most columns in the table) have been estimated: the calculation is based on the assumption that buildings belonging to different year-of-construction segments are all distributed following the general trend, shown in Figure 2-3B. An example is given in footnote 4 in the next page.

Table 2- 3: Number of multi-family dwellings according to year-of-construction segments and estimated values of number of dwellings belonging to each climate zone for each time range. Reference year: 2005.

Sources: (SCB, 2012b; SCB/Energymyndigheten, 2006).

Year-of-construction segment	Whole country	Climate zone I[4]	Climate zone II[3]	Climate zone III[3]
-1920	129 000	7 740	12 900	108 360
1921-1940	245 000	14 700	24 500	205 800
1941-1960	651 000	39 060	65 100	546 840
1961-1970	600 000	36 000	60 000	504 000
1971-1980	324 000	19 440	32 400	272 160
1981-1990	199 000	11 940	19 900	167 160
1991-2000	160 530	9 632	16 053	134 845
2001-2005	65 897	3 954	6 590	55 353
N/A	22 535	1 352	2 254	18 929
Total	2 396 962	151 611	245 665	1 999 686

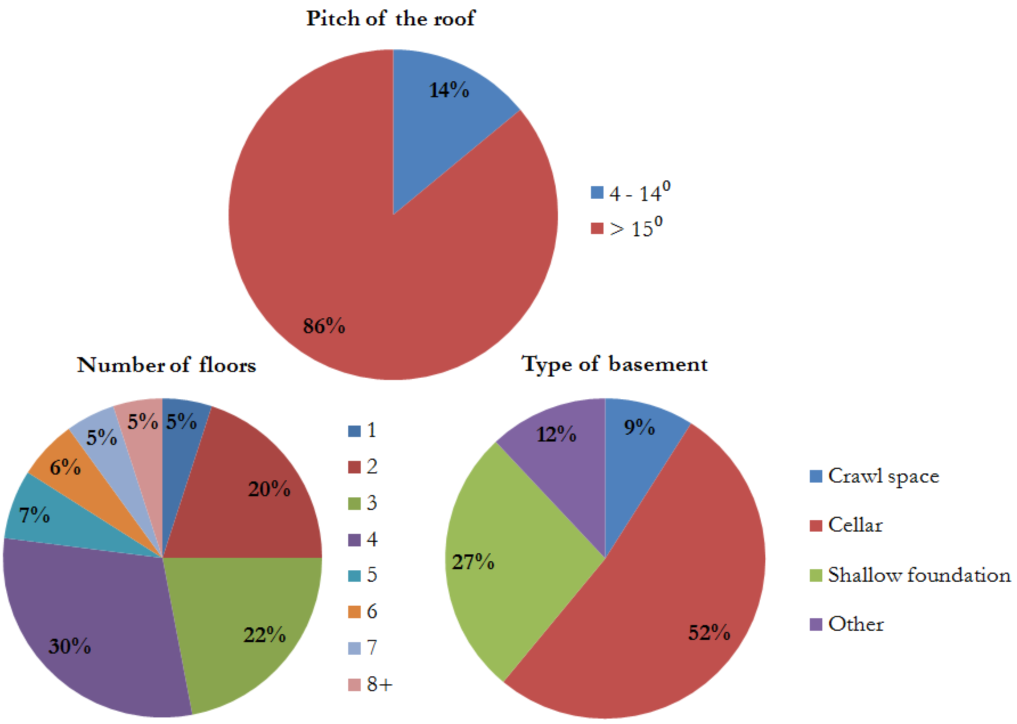

Figure 2- 4: Examples of varying architectural features on Swedish multi-family buildings: pitch of the roof, number of floors, and type of basement, expressed in percentage.

Source: (Boverket, 2010).

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[4] Estimated values. E.g., number of dwellings of climate zone I and reference segment Ref1 (-1920) is obtained by calculating the 6% (i.e. the total number of dwellings located in climate zone I) of the number of dwellings belonging to the segment Ref1: 129 000*0.06=7 740.

Figure 2-4 shows statistical information on prevailing (> 50%) and non-prevailing (< 50%) architectural features needed to be included in the models and affecting the energy performance of buildings. The values indicate the percentage of multi-family buildings having that specific element. The components included in the models are the major ones that singularly or together accounts for more than 50% within a category. For this reason, considering the number of floors, only buildings with two, three and four floors (above ground) are planned to be modelled.

Figure 2-5 shows a scheme of the planning phase prior to data analysis based on the selection of the most significant data. Three major models are intended to be developed reflecting the Swedish climate zones. For each of them, eight sub-models (second level) are designed for each year-of-construction segment, each of which is characterised by different technologies, and therefore differs in terms of insulation, i.e. u-values, reported in Table 2-2. The third-level differentiation is strictly dependent on statistics: if one architectural feature is present in more than 50% of the buildings, only one model is planned, with that specific feature being representative for the entire building stock. If none of the elements within a category is present in more than 50% of the building, more models are considered to be needed. In fact, for each reference segment, additional sub-models need to be developed in order to take into account the number of floors of buildings.

It is important to note that this overview is intended to exclusively reflect the data collection process and disregards further changes discovered to be necessary during the data analysis phase.

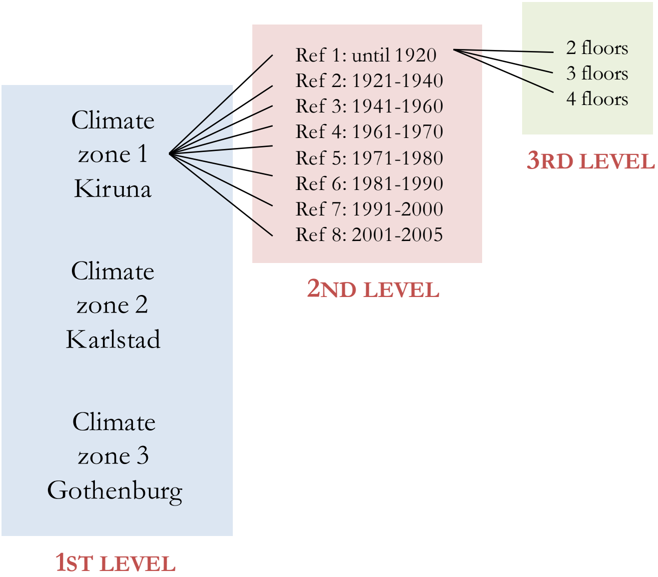


Figure 2- 5: Evaluation scheme of the modelling phase based on data collection. Three main models are planned according to Sweden's climate zones, each of them can be divided into 8 sub-models, reflecting the year-of-construction segments and therefore different technologies and construction materials, hence u-values. The third level differentiation is founded on non-prevailing features that needs to be included in the modelling scenarios.

2.1.3 Economic and environmental factors

Economic and environmental elements related to multi-dwelling buildings are key inputs for the analysis through the EEB_Sweden modelling tool. The values are crucial elements for policy scenario simulations that foresee changes in building regulations, energy prices increase, carbon taxes, etc. Additional information is provided in Section 2.2.2.

Economic factors, such as the fuel and equipment costs were already included in the work by Mundaca et al. (2010a, 2010b), where the EEB_Sweden model was developed to study the Swedish residential sector. These values are reported in this analysis without undergoing additional research.

Table 2-4 shows the emission factor values and prices for district heating, electricity and natural gas used in the residential sector.

Average values for emission factors have been calculated from ranges provided by the Swedish Environmental Protection Agency (2003a, 2003b). Data can in fact vary sensibly according to the type of fuel and technique used both to heat the water for district heating and warm water distribution, and to produce electricity. The Nordic energy mix defined by SEPA (Naturvårdsverket, 2003a, 2003b) and by the European Topic Centre on Air and Climate Change (ETC/ACC, 2003) was used for this purpose.

Table 2-4 also lists the prices of each form of energy as they were in 2005. These values include grid charges, taxes and VAT. Moreover, prices are expressed in US dollars in order to fit the requirements of the EEB model.

Table 2- 4: CO_2 emission factors and prices for different energy forms used in the multi-dwellings residential sector.

Sources: Indicated in the table.

Form of energy	**Emission factor (Kg/kWh)**	**Source**	**Price (US$/kWh)**	**Source**
District heating	0.095	(Naturvårdsverket, 2003a)	0.08	(Mundaca & Neij, 2010a)
Electricity	0.075	(Naturvårdsverket, 2003b)	0.22	
Natural gas	0.387	(ETC/ACC, 2003)	0.09	

2.2 Methods for data Analysis

Energy performance analysis is the central stage of this work. It consists in the use of the modelling software eQuest, able to generate yearly energy consumption scenarios based on detailed building technologies. The outcome of this study represents the input for the implementation of the EEB_Sweden v 1.0 tool and further the policy simulation analysis on multi-family buildings in Sweden.

2.2.1 eQuest

Designed in 1998 by James J. Hirsch and Associates (2010b), eQuest is considered as one of the most sophisticated building energy use simulators. eQuest is a development of the older energy analysis tool DOE-2, created in the late 1970s at the Lawrence Berkeley National Laboratory, and considered powerful but too complicated and time consuming. On the contrary, eQuest with its simplified interface, wizards and standard defaults, can be used by both new and experienced users allowing multiple analysis: from calculating basic energy performance systems to developing detailed life-cycle scenarios. (IDL, 2011)

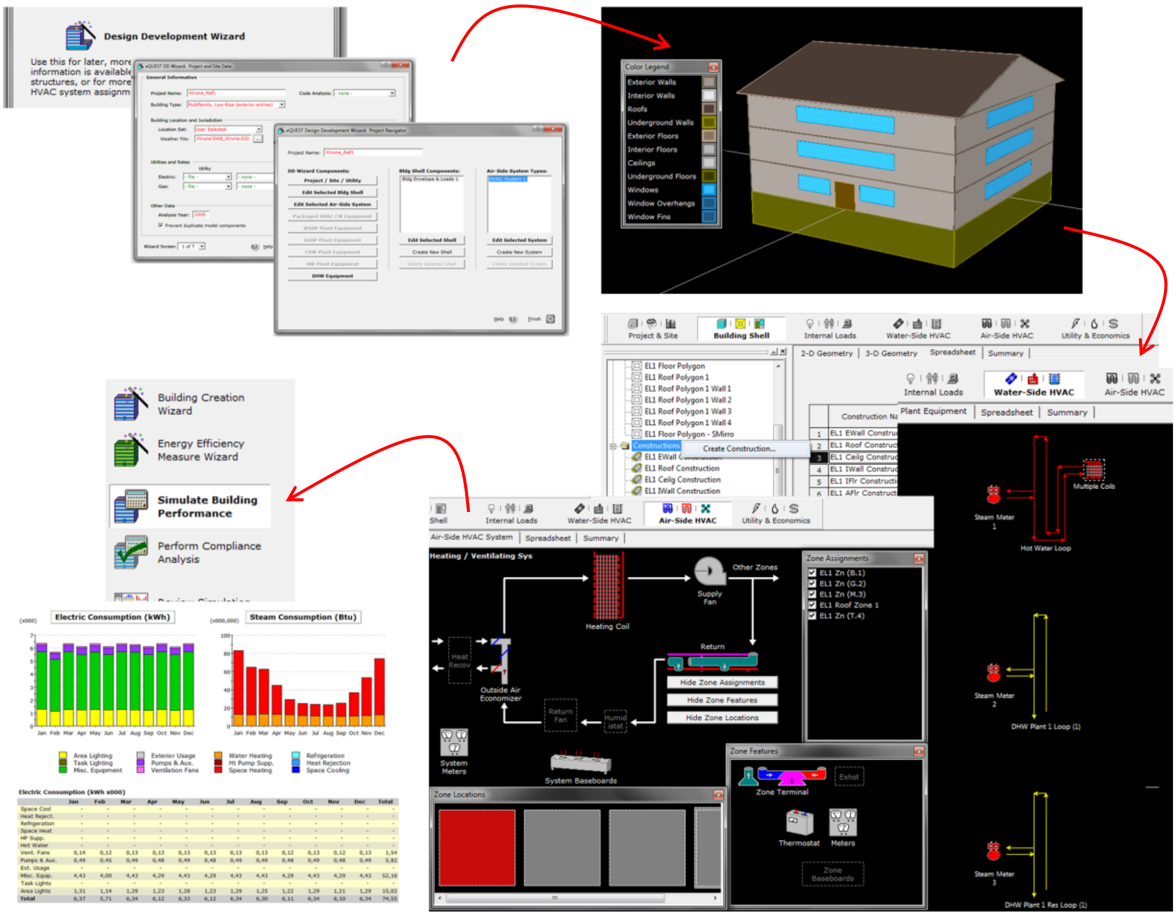


Figure 2- 6: Overview of some steps of the simulation process with eQuest. Energy performance of a building is retrieved by first inserting specific information on the building characteristics through a wizard; then, by manually creating new features or changing data regarding the project site, building shell, internal loads, water-side and air-side HVAC system, utility and economics (if desired); finally, by simulating the building performance.

Source: eQuest v.3.64, copyright (c) 1998-2010 by James J. Hirsch.

Using the weather data for the site under study, eQuest performs hourly analysis of the energy consumption of a single building by following several calculation steps within four main areas: loads, systems, plant and economics (Hirsch & Associates, 2010a). The simulation process starts by inserting detailed information on the building location, envelope characteristics, fenestration, HVAC system, occupants' schedules, lighting equipment, and utility rates through a wizard that has pre-set defaults, mainly US standards. Then, it allows to manually modify parameters, and add/remove elements through a detailed interface. Finally it creates a building model for which an energy performance report can be retrieved. A snapshot of the process' highlights is shown in Figure 2-6.

It is important to point out that building energy modelling is a simplified representation of the energy consumption of buildings and should not be considered as a perfect science. Regardless of its accuracy, the model will still differ from the real building energy usage. For this reason, a ±15% margin of error should be applied for all results.

Modelling the Swedish multi-family residential sector

eQuest was chosen in order to model Swedish multi-family buildings and extrapolate energy performance values of single equipments and technologies.

While the energy consumption for space heating and warm water and the electricity use of households are provided by the Swedish Energy Agency and Statistics Sweden, the energy use attributed to single equipments can only be retrieved by modelling a scenario that comprehends these elements, understands their interconnection and mutual influences, and calculates their individual contributions.

In this work, eQuest allowed to model buildings characterised by different technologies and retrieve specific disaggregated data for space heating and space cooling equipment, ventilation equipment and distribution, lighting and cooking equipment, water heating system, large and small plug devices. These elements, representing input categories in the EEB_Sweden modelling tool, were used in the second phase of the analysis to run the policy scenario simulations.

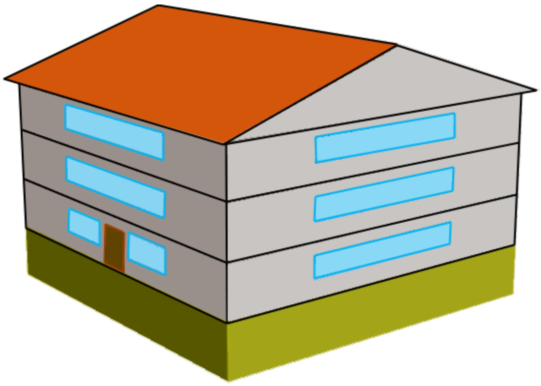
2.2.1.1.1 Baseline building model

In general, the multi-family residential sector is very complex: buildings differ in shape, height, orientation, location, age, fenestration area, etc., not to even mention construction materials and technology, already described in the data collection section. Therefore, the most challenging task of the energy performance analysis with eQuest was the development of the "average building" type, here referred to as "baseline building model", comprehensive enough to incorporate key features, to easily interchange elements, but still being simple and adaptable to the whole Swedish multi-family stock.

For this purpose, the average multi-family building defined in the recent report published by Boverket (2010), was set as starting point. The average multi-family building consists of three floors and a cellar. The total heated area (A_{temp}) is 1426 m^2, including apartments and common areas, such as laundry room, corridors and storage rooms. In the building there are 14.55 apartments, each of them with an area of 68 m^2 and with 1.7 occupants. (Boverket, 2010) In addition, prevailing features, discussed in the previous section, were attributed to the average building model. Elements such as building orientation, fenestration area and orientation, and roof pitch were set once and used as constants throughout the modelling process. This allowed the creation of a dynamic building shell where variables are easily interchanged among each other. In this specific context, the variables refer to the climate zones and to the reference segments – with their unique technology configuration (see Table 2-2).

Figure 2-7 shows the common features of the baseline building models created with eQuest. On the right-hand side of the figure, data characterising the model is indicated.

Multifamily building - baseline model



3 floors + cellar (underground)
building orientation = N
A_{temp}=1426 m²
$A_{windows}$=25% of A_{walls}
2 entrance doors
20° pitched roof
15 dwellings located on the three above ground floors
68 m²/apartment

Figure 2- 7: Illustration and main common features of the multi-family building baseline model.

Source: eQuest v.3.64, copyright (c) 1998-2010 by James J. Hirsch.

In order to assess the energy performance of the Swedish multi-family building stock, 24 models were created initially. In particular, 8 models, each of them reflecting one specific year-of-construction segment, were developed for each climate zone (I, II and III). The outcome was compared and benchmarked to the existing statistics on energy use in multi-family dwellings provided by the Swedish Energy Agency and Statistics Sweden (SCB/Energymyndigheten, 2006), and by Intelligent Energy Europe (2012), that developed the project TABULA on building stock energy assessment in EU member countries. Results are reported and discussed in detail in Chapter 3.

2.2.1.1.2 Sensitivity analysis

Additional models were created in order to measure how much the energy consumption differed from the baseline calculations if some elements were changed. In other words, this sensitivity analysis aimed to assess whether the baseline models could represent the total Swedish multi-family stock within a reasonable range of error (±15%) or if additional models were needed in order to make the study more accurate.

For this purpose, these additional analyses were performed:

- Two climate variations on the baseline models: one where Stockholm was used as representative city for climate zone III instead of Gothenburg and the other where Östersund was used to stand for climate zone I instead of Kiruna.

- Two new building shells composed of two and four floors. In fact, these two building typologies reflect respectively the 20% and 30% of the total Swedish multi-family stock. Therefore, it is important to assess that the average energy consumption per square metre does not change significantly, i.e. more than the range of error ±15%, compared to the baseline values calculated for the three-floor reference building, in order to be able to use the latter as representative for the whole stock.

2.2.1.1.3 Permutation models for EEB scenarios

The use of eQuest was also extended to calculate the energy performance of improved/new technologies, not yet present in Swedish multi-family dwellings, but that will eventually be included in the future. In fact, in order to understand how the energy consumption patterns of the building stock will develop, changes in technology and improvements in energy efficiency have to be taken into account. For this reason, the EEB model lists a series of permutations that differ from the current situation, for instance in terms of envelope insulation, HVAC system and electronic equipment. These permutations are included in the scenario analysis and will be further discussed in the next chapter. For this reason, for each baseline model, specific parameters, reflecting the EEB permutations, where modified and new energy values were extrapolated.

2.2.1.1.4 Main assumptions

During the data analysis with eQuest, several assumptions were considered:

- N/A dwellings represent apartments for which no data have been collected. During the analysis, the N/A dwellings were allocated to the reference segments and climate zones following the distribution trend of the other dwellings.

- The energy consumption of the whole building is attributed to the dwellings inside that building. Therefore, energy use by corridor lights and laundry facilities, for instance, are also included in the consumption of the building apartments.

- All models share the same system for heating and domestic hot water, i.e. district heating. Since it is a central system, the heating unit (e.g. boiler) is not present in the building. Therefore, the heat source cannot be modelled. In order to calculate the energy consumption for heating and domestic hot water, a virtual system, composed of a steam meter and a heat exchanger, is inserted instead. However, this approach has its limitations: the energy consumption equals the consumer demand and energy losses occurring at the central site and in the piping system are not directly taken into account. In order to calculate these losses one should know the types of equipment used by the central system as well as how many buildings and households are connected to that DH network. This is a very challenging task, especially considering the geographical scope of this thesis. Therefore, losses have been incorporated in the building model by changing the steam meter efficiency and the temperature losses in the internal heating and domestic water pipes. Statistical data for heating and hot water consumption (SCB/Energymyndigheten, 2006) were employed as reference in order to adjust losses and obtain consistent consumption levels.

- Simplified constructions for walls, roof, floor, doors and windows were used in the model, i.e. only u-values were employed to characterise these units, while material type and thickness is neglected.

- Shading effects by other constructions lying in proximity of the building under study were neglected.

- Electricity use in households is independent from the building location (climate zone). The statistical average consumption level, i.e. 40 kWh/m^2 (Energimyndigheten, 2005) was used as reference to calibrate the model. However, electricity consumption varies among reference segments. Variations are explained by the presence of more or less energy efficient appliances in buildings. This distribution is based on assumptions and summarised in Table 2-5.

Table 2- 5: Assumptions regarding household electricity-driven appliances and systems divided by year-of-construction segment.

	Ref 1	**Ref 2**	**Ref 3**	**Ref 4**	**Ref 5**	**Ref 6**	**Ref 7**	**Ref 8**
Lighting	Incandescent	Incandescent	Incandescent	Incandescent	CFL	CFL	CFL	CFL and LED
Cooking	Electric stove	Electric stove	Electric stove	Electric stove	Electric stove	Electric stove	Convective electric stove	Convective electric stove
Large plugs	Central washer and dryer, in-unit dishwasher	Central washer and dryer, in-unit dishwasher	Central washer and dryer, in-unit dishwasher	Central washer and dryer, in-unit dishwasher	Central washer and dryer, in-unit dishwasher	Central washer and dryer, in-unit dishwasher	In-unit washer, dryer, and dishwasher	In-unit washer, dryer, and dishwasher
Small plugs	Standard efficiency	Standard efficiency	Standard efficiency	Standard efficiency	Standard efficiency	Standard efficiency	Energy star appliances, LCD monitors and TV	Energy star appliances, LCD monitors and TV
Ventilation	N/A	N/A	N/A	N/A	Mechanical exhaust	Mechanical supply+exhaust w air recovery	Mechanical exhaust	Mechanical exhaust

2.2.2 The EEB model

The EEB model was created by Robust System and Strategy LLC in the frame of the Energy Efficiency in Buildings (EEB) project by the World Business Council for Sustainable Development (WBCSD).

Started in 2006, the EEB project aimed to analyse the energy consumption patterns of the residential sector and to understand what is needed to reduce 80% of its energy use by 2050. (WBCSD, 2012) It is acknowledged that the best available technology today has the potential to dramatically improve energy efficiency in buildings. However, the progress achieved so far is not enough to reach the 2050 carbon emissions target, main reasons being market and policy failures, and behavioural barriers. Therefore, the need for a tool that could analyse the present and future energy consumption scenarios, and specifically address the residential sector, was recognised - and the EEB model created.

The EEB model is based on a bottom-up approach; it is designed to consider current technology configurations and energy demand distinctively for the residential sector, and simulate future scenarios, where policy actions can be combined with construction options and consumer decisions. (Mundaca & Neij, 2010a)

In this work, future energy consumption patterns and carbon emissions of the multi-family residential sector in Sweden are analysed with EEB_Sweden v. 1.0, which was developed by Mundaca et al. (2010a, 2011), in order to address the Swedish residential sector, and based on the above mentioned general platform. As mentioned before, the EEB_Sweden model is still under development and much of the work at hand aims to support its further development.

Building blocks of the model

The EEB is a modelling platform created in Microsoft Excel, composed of six inter-linked modules: beside an input and output section, each of the remaining modules is addressing a specific aspect of the residential sector, i.e. cost, energy, decision and stock. (Mundaca & Neij, 2010a) A schematic view of the EEB analysis process structure is shown in Figure 2-8.

In the next paragraphs, the EEB model building blocks are explained in detail. This description is entirely based on a personal communication with Luis Mundaca (2012) and on his work regarding the development of the Swedish version of the EEB platform (2010a).

The first element is represented by the input module (sketched in red, on top of Figure 2-8). It is further divided into five units that comprise technology construction packages (i.e. types of technologies present in the residential sector under analysis), operational behaviour (user consumption levels, for instance), policy environment (including subsidies and carbon taxes), exogenous variables (such as energy price) and decision criteria (financial and non-financial).

The cost module entails all cost-related aspects regarding the residential building. This includes both quantitative data on the prices for specific technology elements, their installation and maintenance, and qualitative information as indoor environmental quality, technology ease of use and installation, and appearance.

The energy module with its three sub-fields (in violet in Figure 2-8) allows inserting energy values corresponding to each technology installed in the dwellings. More details are given in the section “Swedish multi-family dwellings analysis through EEB_Sweden v1.0”.

The technology choice decision and ranking module comprehends several groups of technology combinations that differ, for instance, in terms of HVAC system, envelope characteristics and internal loads. Apart from attributing specific technologies to the current residential stock, a list of permutations - in form of technology packages – are included and utilised for the analysis of future configurations, where, to mention an example, light bulbs and cooking appliances are more efficient, the building envelope is better isolated and solar energy is used to heat the domestic hot water.

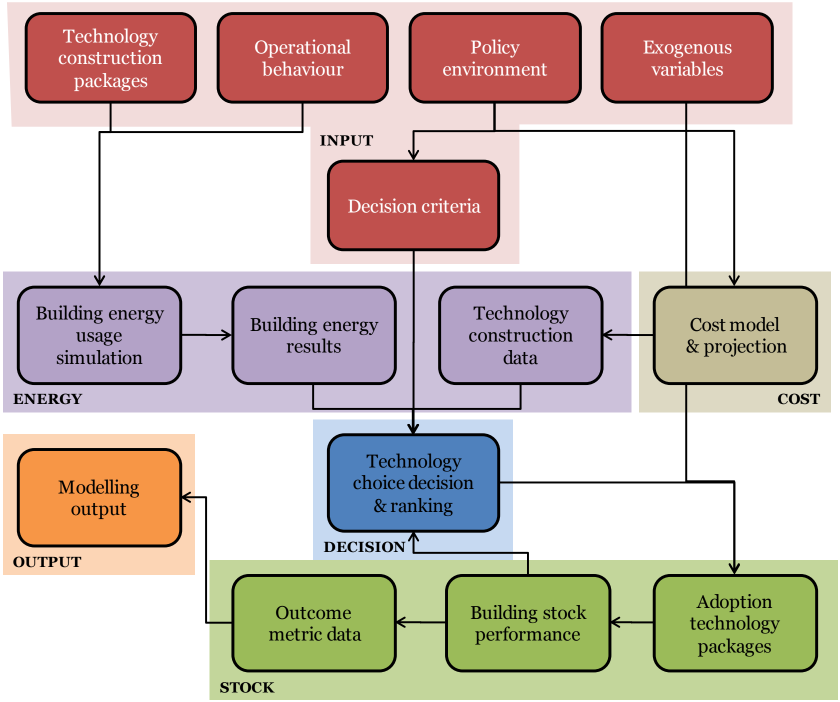


Figure 2- 8: EEB modelling methodology, divided by modules.

Source: Adapted from Mundaca et al. (2010a).

A crucial aspect of the technology choice module is the decision framework that lies behind the adoption of one technology-package over another. The decision framework includes parameters able to influence technology preferences: these are basically divided in financial (e.g. investment cost) and non-financial criteria (e.g. indoor environmental quality). Moreover, the role these two criteria can play in future scenarios can be changed by controlling their weights. In addition, technology choice can be further influenced by the policy environment that reflects current and future actions in the residential stock, such as subsides and carbon taxes. Finally, the framework also takes into account external variables such as carbon emissions and energy prices. The technology choice and ranking module is probably what makes EEB unique if compared to most other policy analysis models that only uses technological and economical parameters as decision criteria.

The stock module (in green in Figure 2-8) contains data regarding the current number of buildings present in the stock (divided in categories - according to needs), the buildings' growing and destruction rates, and data regarding the number of dwellings being refurbished (and therefore going through a decision process for a new technology package) every year. These elements permit to foresee how the stock shape looks like in the future.

Last, the output module (in orange in Figure 2-8) allows to assess the energy consumption and carbon emissions per building and for the whole sector, the investment and maintenance costs faced by households, and the costs related to the specific policy scenario under analysis.

Main assumptions

The EEB model takes into account a few assumptions, listed in the report published by Mundaca et al. (2010a). These can be summarised as follows:

- Dwellings are considered independent blocks in the model. Decisions taken at the dwelling-level are independent from each other and strongly steered by economic factors. However, qualitative criteria are also included in order to mimic the rationality of individuals which is limited by the information they have.

- The model considers on-site electricity generation and emission factors connected to the energy demand. However, it neglects information on the production at the district level (as mentioned for the eQuest model).

- Technology permutations depend on prices.

- Reference year is 2005 and the model performs projections until 2050. In this time range, resources and demand are considered infinite, but can be limited by putting constraints in the model.

Swedish multi-family dwellings analysis through EEB_Sweden v1.0

EEB_Sweden v 1.0 was specifically shaped to model the Swedish residential sector. Still containing all the building blocks previously described for the general system, it focuses on the two main Swedish residential categories: single- and two-family houses, and multi-family dwelling buildings.

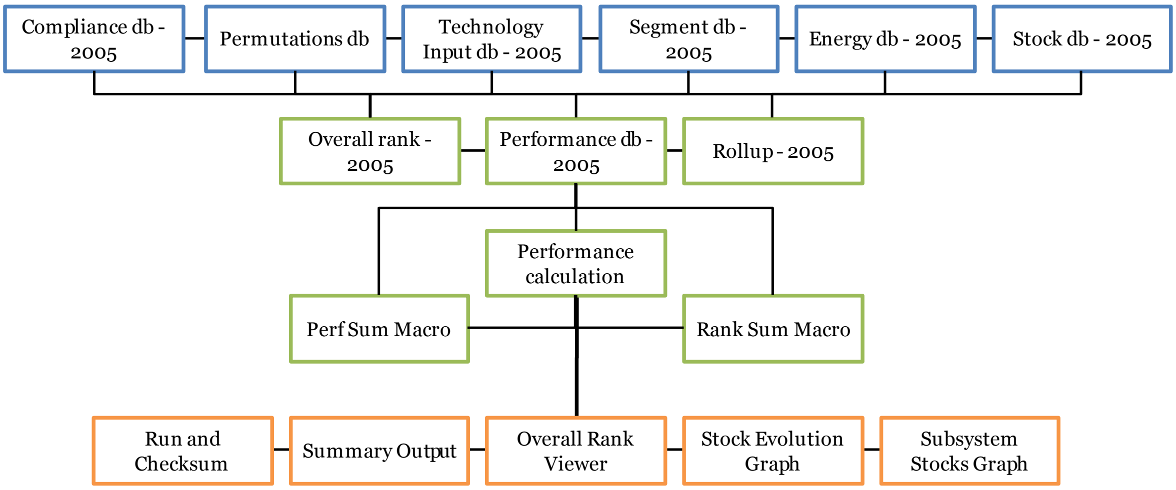


Figure 2- 9: Composing elements of the EEB_Sweden model. Each box represents an excel sheet of the platform. Key inputs and definitions are included in the sheets represented by blue boxes, calculation modules by the green boxes and outputs by the orange boxes.

Source: Adapted from written material obtained by Luis Mundaca during a personal communication (2012).

In this work, EEB_Sweden is used to analyse the multi-family residential sector, considering 2005 as the baseline year. The platform is divided in several inter-linked sheets that need to be properly compiled to perform scenario simulations. These sheets are illustrated in Figure 2-9: the blue boxes represent input sheets, the green are calculation sheets, and the orange correspond to output sheets. The solid lines indicate how sheets are connected and dependent to each other.

In this work, the analysis process with EEB_Sweden can be summarised in three steps: data incorporation, check of errors, and strategy runs - with consequent collection of output figures. The first step is the most time-consuming phase and can be described as follows:

- *Assemble eQuest models output data into the technology-packages.* This step consists in gathering the energy values obtained with eQuest and inserting them into the Energy db -2005 sheet. The technologies for which the energy use needs to be specified are: space heating and cooling equipment, ventilation, HVAC controls, water heating, lighting equipment and controls, cooking, small and large plugs, solar PV, solar thermal. Data is indicated as yearly energy consumption per dwelling, where the dwelling is defined as a 68 m^2-apartment. Values are specified for the current stock, i.e. for the eight year-of-construction segments[5], and for the permutations that comprise a range of 52 to 98 technology packages, i.e. improvements, per segment. An example of permutations is reported in Appendix A.

- *Insert statistical data.* Total number of buildings and number of buildings per reference segment, area, growth and demolition rates, refurbishment system, emission factors and costs for each energy form are included in the model.

- *Insert cost data.* No new cost data was gathered. Average values previously indicated by Luis Mundaca (2012) in the model EEB_Sweden are adopted.

An in-built control system (checksums) allows identifying errors in the model – before starting the strategy runs. This tool is present on each sheet of the platform and results are also visible on one specific sheet – as shown if Figure 2-9.

Finally, it is possible to select the desired policy scenarios, for each of which a specific excel file will be created. Once the strategy runs are completed, the output data from each scenario file can be retrieved.

2.2.3 Scenario analysis

In general, a scenario can be seen as the projection of a series of possible events. In this context, a policy scenario has the ability to provide a vision of future trends driven by that specific policy, and can therefore be seen as a tool able to guide policy makers and analysts towards more effective measures.

This section aims to present the scenarios analysed in this thesis. The selection is strongly based on the previous work of Mundaca et al. (2011) where a few policy intervention were chosen since considered more relevant to analyse the future Swedish residential market.

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[5] As already listed in § 2.1.1; Ref1: -1920, Ref2: 1921-40, Ref3: 1941-60, Ref4: 1961-70, Ref5: 1971-80, Ref6: 1981-90, Ref7: 1991-2000, Ref8: 2001-05.

Moreover, by selecting the same scenarios for this study, it was possible to analyse similarities and differences, such as assessing whether the incorporation of simulated energy data obtained with eQuest affects the scenario results differently from the use of average EU-15 data, employed in the reference work (Mundaca & Neij, 2011).

In the next sections, a brief explanation for each scenario is given, together with the reason why it was chosen.

Baseline scenarios

The departure point for developing alternative baselines or counterfactuals lies in uncertainties about future policy developments. In this thesis, the development of alternative counterfactuals is critical in ascertaining the robustness and sensitivity of the modelling outcomes to the assumptions and limitations embedded in different counterfactuals and simulated policy instruments. To that end, two baselines were developed.

2.2.3.1.1 Baseline 1 – Market response

The *Marker response* scenario represents the hypothetical future where no policy instruments are adopted and energy prices remain constant. Moreover, equipment cost variations are small and efficiency improvements are undertaken only when refurbishment takes place. This setting is considered as a reference case in order to be able to assess how successful policy actions can be in terms of reduction in energy consumption.

2.2.3.1.2 Baseline 2 – Current Swedish energy policy

This scenario simulates the measures taken by the Swedish government to improve energy efficiency in the residential stock. These include regulations on how buildings should be constructed in order to reduce energy use, and grants for the installation of solar cells or the conversion to a more efficient heating system. (Energimyndigheten, 2009) The EEB model simulates this policy by assuming a 65% reduction in the investment cost for implementing solar PV and a 35% reduction for converting the heating system.

It has to be pointed out that these financial supports ended in 2011. In case of renovation, maintenance, conversion or extension, individuals have now to rely on tax reductions called ROT deduction. (Energimyndigheten, 2011b)

Similarly to the "Market response" setting, this scenario represents a baseline for other simulated policies.

Scenario 1 – Net Zero Energy Buildings (NZEB)

In this scenario buildings constructed after 2020 must be energy neutral, i.e. energy consumed and produced within the building area must be equal to zero, on a yearly base. This simulation uses as a baseline the scenario Current Swedish energy policy.

This scenario is interesting in the perspective of the EU recast Directive on Energy Performance in Buildings (2010/31/EU) that requires all new buildings constructed after 2020 to be nearly zero energy buildings, i.e. buildings with very high energy performance (e.g. A-class buildings, see Table 2-6). (ECEEE, 2010)

Scenario 2 – 10x raise in energy prices

This scenario considers a 10 times increase in fuel prices. This increase occurs step-wise to reach the final 10x raise in 2050. All other variables will be kept as in the "Current Swedish energy policy" baseline. Fuel prices are very likely to increase, but probably not as much as ten times in the time frame set for the analysis. However, it is interesting to study such an extreme situation since the EEB model also takes into consideration consumer behaviour, which, in this particular case, can influence the outcome. Baseline 2 is adopted as baseline.

Scenario 3 – Financial incentives

This scenario reflects a situation where beside current energy policy, incentives for efficient buildings are provided. Following the official EU ranking system, buildings can be categorised from A to G, depending on their energy use, as shown in Table 2-6.

Table 2- 6: EU energy efficiency ranking system for buildings according to their yearly energy consumption per unit area.

Class	**Energy consumption** ($kWh/m^2/yr$)
A	≤ 50
B	51-90
C	91-150
D	151-230
E	231-330
F	331-450
G	> 450

Economic incentives are given when constructing new efficient buildings; in particular, a 50% reduction in capital and labour cost for A-class buildings, and a 25% for B-class buildings.

Scenario 4 – Carbon tax, bans and incentives

This simulation reflects a combination of actions aimed to obtain a transformation of the residential sector. In the time span 2005-2050, a 30$ carbon tax per metric ton of CO_2 emitted is included. Moreover, economic incentives for new A- and B-class buildings are provided as in scenario 3. Furthermore, a ban is set for refurbishing into or constructing E-, F- or G-class buildings, i.e. with yearly energy consumption above 230 kWh/m^2. The baseline setting is number 2.

Including non-techno economic determinants

One of the main properties of the EEB platform is the possibility to incorporate non-financial aspects in the modelling process, in order to mimic a more realistic system. In specific, when a new technology is chosen, both financial-technical and non-financial aspects are considered and their weight can be varied in the model. Moreover, a score from 1 (low) to 5 (high) can be assigned to qualitative components, such as indoor environmental quality, technology ease of use and installation, and appearance.

Similarly to Mundaca et al. work (2011), the qualitative criteria were included in the above mentioned scenario analyses. Choices were set to be based on 50% technical-financial characteristics and 50% on non-financial aspects. Moreover, the score assigned to qualitative aspects was set to 3 for indoor environmental quality, reliability and predictability, ease of use and installation, appearance, and energy and atmosphere.

3 Results and discussion

The most significant results of the analysis performed with eQuest and EEB_Sweden_v1.0 is reported in this chapter.

3.1 Energy modelling with eQuest

3.1.1 Estimated current energy performance

The energy performance of multi-family buildings, belonging to eight different year-of-construction segments and located in the three Swedish climate zones, was calculated in eQuest from the baseline building models, already discussed in the methodology section.

The modelled energy use for heating and hot water is shown in Figure 3-1 and listed in Table 3-1. As expected, consumption levels are higher for older buildings, with worst envelope and fenestration u-values compared to newly built constructions. Moreover, energy use differs sensibly among dwellings located in diverse climate regions.

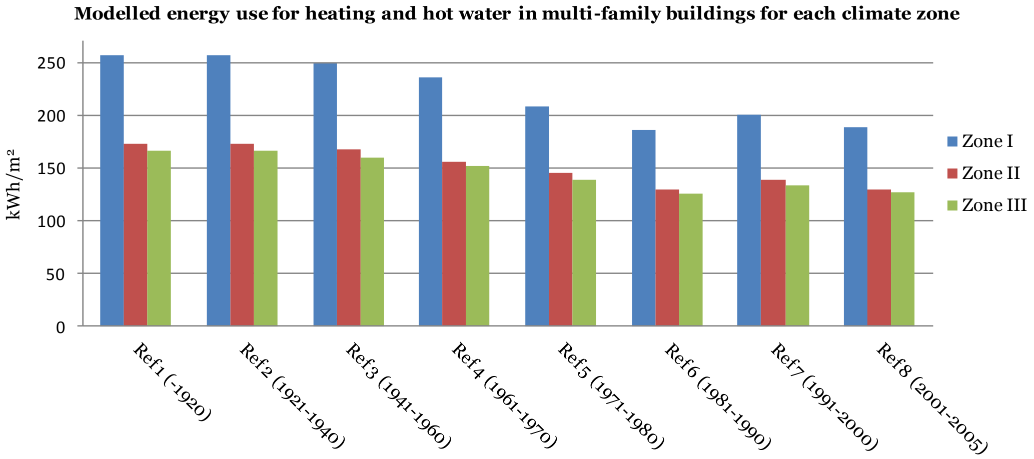

Figure 3- 1: Energy consumption expressed in kWh/m² for heating and hot water in multi-family buildings modelled with eQuest for each reference segment and climate zone.

Table 3- 1: Modelled energy consumption values for heating and hot water in multi-family buildings divided by reference segment and location (climate zone).

Year-of-construction segment	**Modelled energy use for heating and hot water (kWh/m²)** **Zone I**	**Zone II**	**Zone III**
Ref 1 (-1920)	257.2	173.5	165.8
Ref 2 (1921-1940)	257.2	173.5	165.8
Ref 3 (1941-1960)	249.6	167.9	160.2
Ref 4 (1961-1970)	236.2	156.3	151.5
Ref 5 (1971-1980)	208.9	145.2	139.0
Ref 6 (1981-1990)	185.4	129.1	125.5
Ref 7 (1991-2000)	200.0	138.5	133.0
Ref 8 (2001-2005)	188.2	129.8	126.6

For each reference segment, an average value was extrapolated by weighting consumption levels by the number of dwellings in each climate zone:

$$E^{AVG}_{Ref\,(n)} = \frac{\left(E^{I}_{Ref\,(n)} \cdot N^{I}_{Ref\,(n)}\right) + \left(E^{II}_{Ref\,(n)} \cdot N^{II}_{Ref\,(n)}\right) + \left(E^{III}_{Ref\,(n)} \cdot N^{III}_{Ref\,(n)}\right)}{N^{I}_{Ref\,(n)} + N^{II}_{Ref\,(n)} + N^{III}_{Ref\,(n)}}$$

where E is measured in kWh/m^2 and represents, in this particular case, the energy use for heating and hot water per unit area. n ranges from 1 to 8, according to the year-of-construction segment; N represents the number of dwellings; I, I and III stand for the climate regions.

In Figure 3-2, results are compared with the national statistic values of 2005 (SCB/Energymyndigheten, 2006), which was employed, during the modelling process with eQuest, to calibrate the outcome. Although there are visible differences, the deviations are within the 15% range of error defined as the fluctuation to be considered for eQuest results (§2.2.1). Moreover, it is important to point out that models (blue columns) are based on the assumption that all buildings use DH for heating and hot water, which is not the case for measured official values (red columns). Therefore, for comparison purposes, the statistical consumption level (SCB/Energymyndigheten, 2006) for buildings only using DH is also reported in Figure 3-2 (red dashed column).

Results, and statistics, indicate that buildings constructed between 1981 and 1990 are the most efficient. In the model, the most significant energy savings are attributed to the ventilation system, which, differently from all other segments, is equipped with a heat-recovery system that contributes to lower heating demand. This represents a key element to bear in mind when observing the outcome of policy scenario simulations in section 3.2.

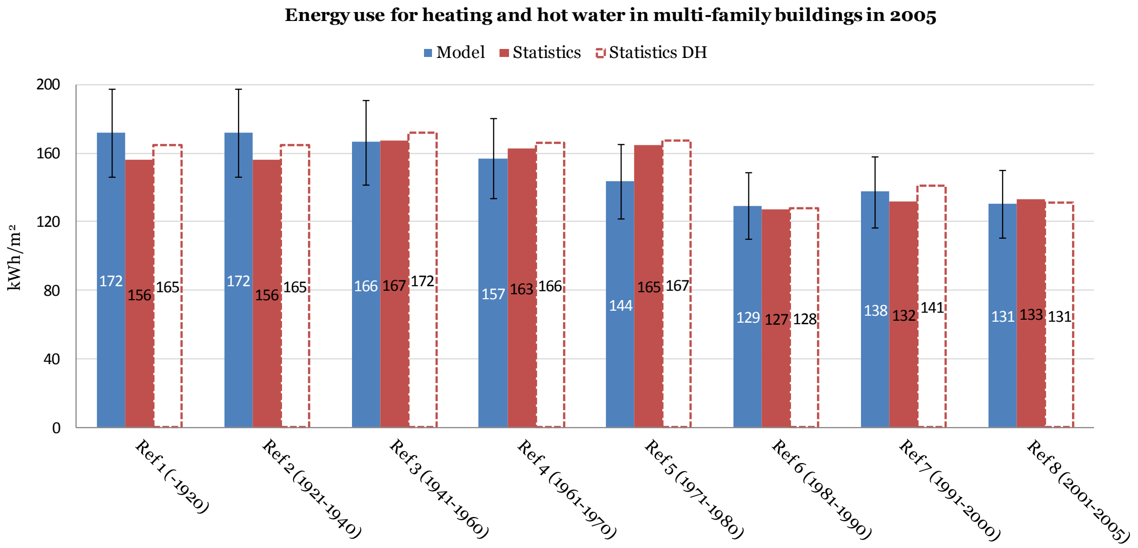

Figure 3- 2: Comparison between estimated and statistical energy use for heating and hot water in multi-family buildings. Blue column correspond to modelled values, red and red dashed column indicate measured data in Sweden in 2005 (SCB/Energymyndigheten, 2006) for all heating systems and for district heating respectively. Error bars correspond to 15% of the modelled values.

Furthermore, energy data from 2005 is highly uncertain since values are based on outdated statistics. The modelling work is instead based on new data collected from the BETSI project (Boverket, 2010). One of the most evident discrepancies between these two official sets of information is the definition of A_{temp}, i.e. the total heated area for multi-family buildings, which is equal to 178 000 000 m^2 according to the Swedish Energy Agency (SCB/Energymyndigheten, 2006) and to 162 928 000 m^2 in the BETSI report (Boverket, 2010) (common areas excluded).

Electricity consumption in multi-family households was calculated combining the eQuest platform with data provided by the Swedish Energy Agency (Energimyndigheten, 2012c) and the energy company Vattenfall (2012), and based on the assumptions indicated in the methodology section (Table 2-5). In accordance with the EEB_Sweden platform, contributions to electricity consumption in households were divided in the following categories: lighting, cooking, large plugs (e.g. washing machine), small plugs (e.g. TV, laptop) and ventilation. Table 3-2 and Figure 3-3 show the outcome of this analysis.

Table 3- 2: Modelled electricity use per unit area in multi-family apartments divided by categories and year-of-contruction segments.

	Electricity use (kWh/dwelling)				
	Lighting	**Cooking**	**Large plugs**	**Small plugs**	**Ventilation**[6]
Ref 1 (- 1920)	704	560	859	783	0
Ref 2 (1921-1940)	704	560	859	783	0
Ref 3 (1941-1960)	704	560	859	783	0
Ref 4 (1961-1970)	704	560	859	783	0
Ref 5 (1971-1980)	514	560	859	783	82
Ref 6 (1981-1990)	514	560	859	783	263
Ref 7 (1991-2000)	514	560	921	578	82
Ref 8 (2001-2005)	330	490	921	578	82

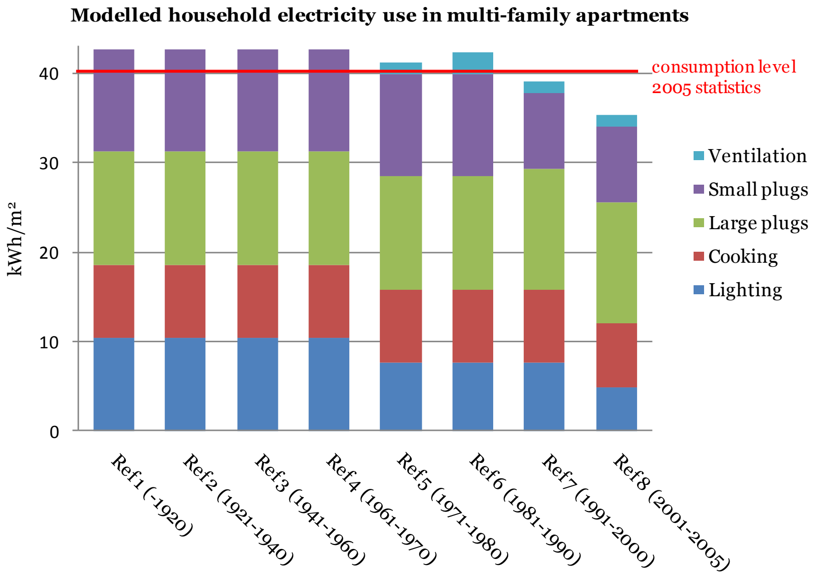

Figure 3- 3: Estimated electricity use per unit area in multi-family apartments, divided by categories. Average consumption level, provided by national statistics, is reported as a red line.

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[6] Electricity consumption of cooking ventilation, e.g. use of blowers, is incorporated in the cooking category.

Figure 3-3 indicates that the modelled electricity consumption is on average above the statistical level registered in 2005, i.e. 40 kWh/m^2 (SCB/Energymyndigheten, 2006).

Disregarding the eventuality of an erroneous choice of average consumption levels and assumption in the modelling phase, one reason that could explain this mismatch is that electricity consumption is calculated for the whole building. Therefore electricity use for lighting corridors and storage rooms, as well as for common laundry facilities is included and distributed evenly among the building apartments.

A weighted average was calculated from the electricity consumption of the eight reference segments. These values were grouped together with the energy use for district heating in order to obtain the total energy use in Swedish multi-dwelling buildings. An illustration of the results is reported in Figures 3-4 and 3-5.

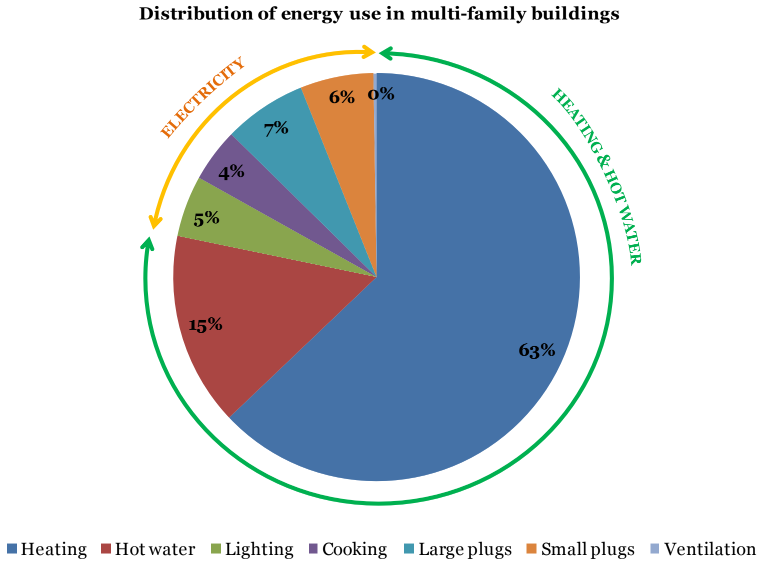

Figure 3- 4: Average contribution of the HVAC system and household appliances to the total energy consumption in multi-dwelling apartments.

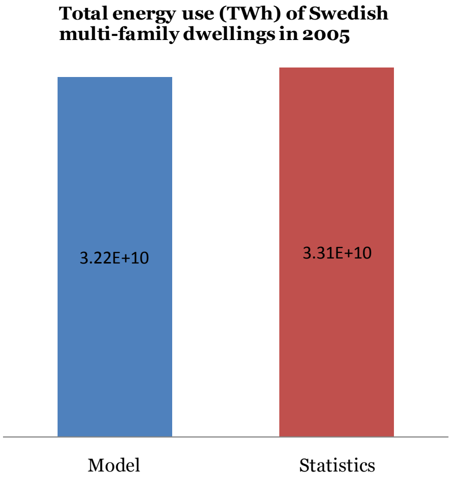

Figure 3- 5: Total energy use in Swedish multi-dwelling buildings in 2005. Blue column represents the modelled value; red column indicates the statistical value retrieved from Energimyndigheten, 2012.

In Figure 3-5, the modelled (blue column) and statistical (red column) total energy use for 2005 are compared. The deviation between measured and modelled value is within a 3% range.

It is important to highlight that during the modelling process, estimated energy values were continuously compared with statistics. Calibration and benchmarking were crucial methods to achieve robust baseline values.

3.1.2 Permutation models

Energy performance of improved and new technologies is modelled in order to allow the simulation of future scenarios with the EEB_Sweden platform. The calculations are based on the existing eQuest baseline building models, where elements such as envelope structure, windows and heating system are improved or replaced with more efficient parts. Results cannot be compared to existing statistical data since the combination of these systems inside buildings are not yet implemented and permutations reflect future actions in the sector. However, energy values for single elements (e.g. efficient LED lighting, solar PV, efficient flat screen TV) can be easily retrieved from commercial websites and brochures that represented, in this work, a reference value for the modelled outcome.

As already mentioned in the methodology section, permutations embody different technology packages with a combination of equipments and measures aimed to improve, energy-wise, the current state of a building. For each reference segment, between 65 and 98 permutation packages were included in the EEB model. Therefore, due to the massive size of data, the results of this analysis are not shown here.

However, an example of the degree of improvement from the baseline value achieved by adopting a technology package is shown in Figure 3-6.

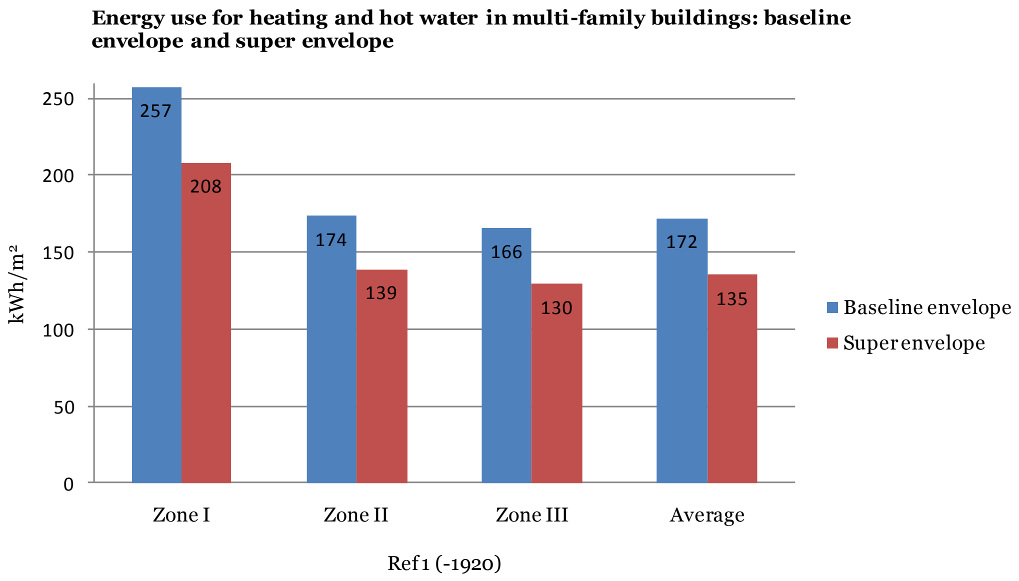

Figure 3- 6: Comparison between the energy use per unit area for heating and hot water in two modelled multi-family buildings belonging to the reference segment Ref 1. The first, represented by the blue columns, is the baseline model, the second, characterised by the red columns, is an improved building with a better isolated envelope, the so-called super envelope.

Here, the energy consumption for heating and hot water per unit area drops considerably when the building envelope is better isolated, adopting a so-called “super envelope”, characterised by the u-values indicated in Table 3-3.

Figure 3-6 compares the energy use for heating and hot water in multi-family buildings belonging to the reference segment Ref 1 considering the standard envelope (blue columns) and a hypothetical improved envelope, i.e. the super envelope. The energy gain attributed to this permutation is approximately 20%.

Table 3- 3: Comparison between u-values: Ref 1 baseline envelope and the permutation super envelope.

		u-value (W/m^{2}K)		
		Roof	**Walls**	**Fenestration**
Baseline	**Standard envelope Ref 1**	0.36	0.58	3
Permutation	**Super envelope**	0.13	0.03	1.3

3.1.3 Sensitivity analysis

In order to ensure a correct choice of baseline building models, two sensitivity analyses were carried out. The outcome is reported in the next sections.

Replacing weather data

Five weather files for the three climate areas are possible to retrieve from the DOE2 database (2001): Kiruna and Östersund for zone I, Karlstad for zone II, Gothenburg and Stockholm for zone III. Kiruna, Karlstad and Gothenburg were selected as representative cities for the climate zones in the baseline building models. In order to assess energy performance variation within a climate region, building models using Östersund and Stockholm representing zone I and III respectively were developed.

Figure 3-7 shows the modelled energy use for heating and hot water in multi-family buildings for each year-of-construction segment. The baseline building model described in the methodology section was used, and only weather data was replaced.

According to the models, the difference in energy performance within climate zone I is not marginal. Energy use in Kiruna is higher than in Östersund, and variations are approximately 26% of the reference value. On the other hand, consumption levels within climate zone III are very similar and can be considered equal in a range of 1%.

Table 3-1 indicates the total energy consumption for heating and hot water in (i) the baseline case, (ii) considering weather data from Stockholm instead of Gothenburg, (iii) replacing Kiruna with Östersund, and (iv) incorporating both weather file variations.

Although energy data for Kiruna and Östersund differ consistently, the number of buildings within zone I only represents the 6% of the total Swedish multi-family stock. Therefore the weight of such a variation on the total energy use for heating and hot water is negligible within a ± 2% deviation from the baseline level, as shown in Table 3-1.

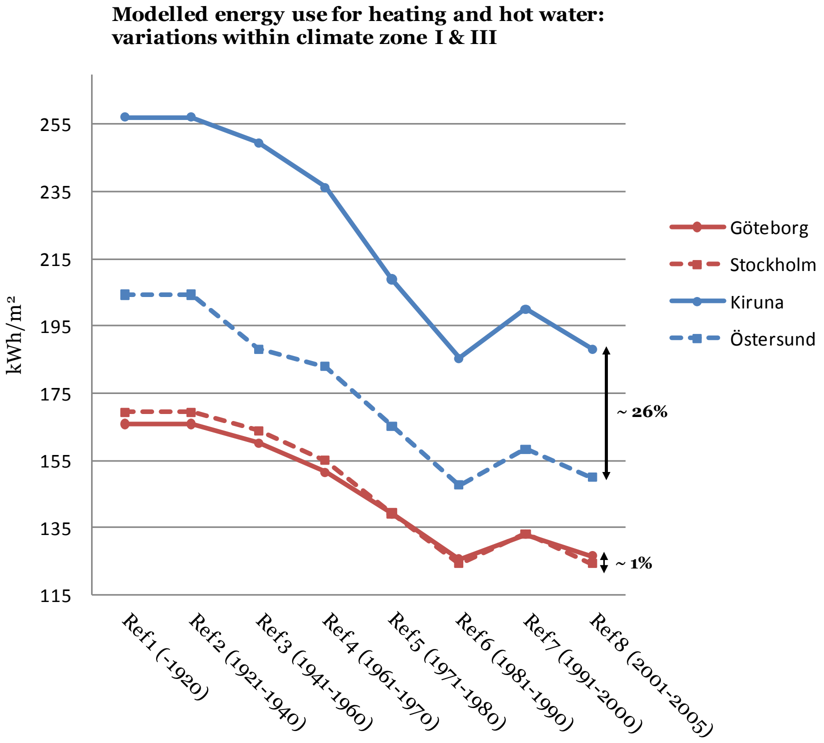

Figure 3- 7: Weather sensitivity analysis. Energy consumption for heating and hot water modelled using weather data from Stockholm (climate zone III) and Östersund (climate zone I). Values are compared to baseline levels, i.e. with weather files from Gothenburg and Kiruna.

Table 3- 4: Outcome of sensitivity analysis on weather data. Energy use for heating and hot water per unit area is reported in the baseline case, and for three weather files permutations.

Energy use for heating & hot water	**Baseline case:** Kiruna, Karlstad & Göteborg	**Permutation 1:** Kiruna, Karlstad & Stockholm	**Permutation 2:** Östersund, Karlstad & Gothenburg	**Permutation 3:** Östersund, Karlstad and Stockholm
Average use (kWh/m²)	155.7	157.7	152.7	154.6
Total use	2.54E+10	2.57E+10	2.49E+10	2.52E+10
Deviation from baseline case		+1.3%	-1.9%	-0.7%

Changing number of floors in building models

According to recently published statistics (Boverket, 2010), buildings composed by two, three and four floors are the most common, representing together 72% of the total multi-dwelling stock (see Figure 2-4).

However, only three-floors buildings were considered in the analysis since the variation of the energy consumption per unit area in respect to two-floors and four-floors buildings can be neglected. This was verified by calculating the energy use per square meter for heating in buildings with two, three and four floors constructed between 2000 and 2005 (Ref 8) and located in the climate zone III (reference city Gothenburg).

Results are reported in Figure 3-8, together with the deviations – in percentage – from the baseline value. As expected, energy consumption for heating is higher for buildings with only two floors, and approximately equal for buildings with three and four floors.

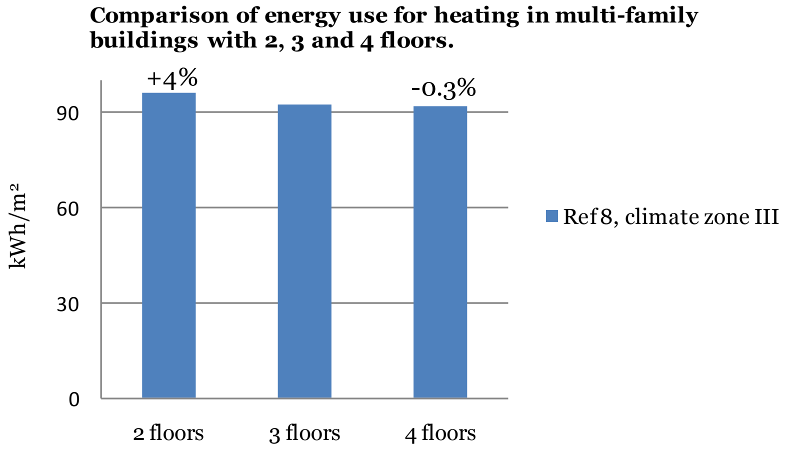

Figure 3- 8: Sensitivity analysis for number of floors in multi-family buildings. Energy use for heating per unit area for 2-, 3- and 4-floors buildings belonging to the reference segment 8 and climate zone III. Energy performance deviations from the baseline building model (3 floors) are expressed in percentage.

3.2 Policy scenario simulations with EEB_Sweden

The aim of simulating policy scenarios with EEB is to analyse, ex-ante, how future patterns in energy consumption in buildings is affected by specific measures that could be adopted by policy makers. Moreover, it is of particular interest to understand which instrument or combination of actions are needed to transform the Swedish building stock in terms of energy efficiency and consumption. Here, results from two baseline and four scenario simulation tests are presented and compared.

3.2.1 Baseline 1 – Market response

The market response scenario reflects the case where no policy instruments are introduced and energy prices are kept the same as in 2005.

Figure 3-9 shows the outcome of this analysis. Primary energy consumption in 2050 has an increase of 380% in respect to the baseline year, 2005. The increase is higher for CO_2 emissions, registering a 411% rise compared to 2005.

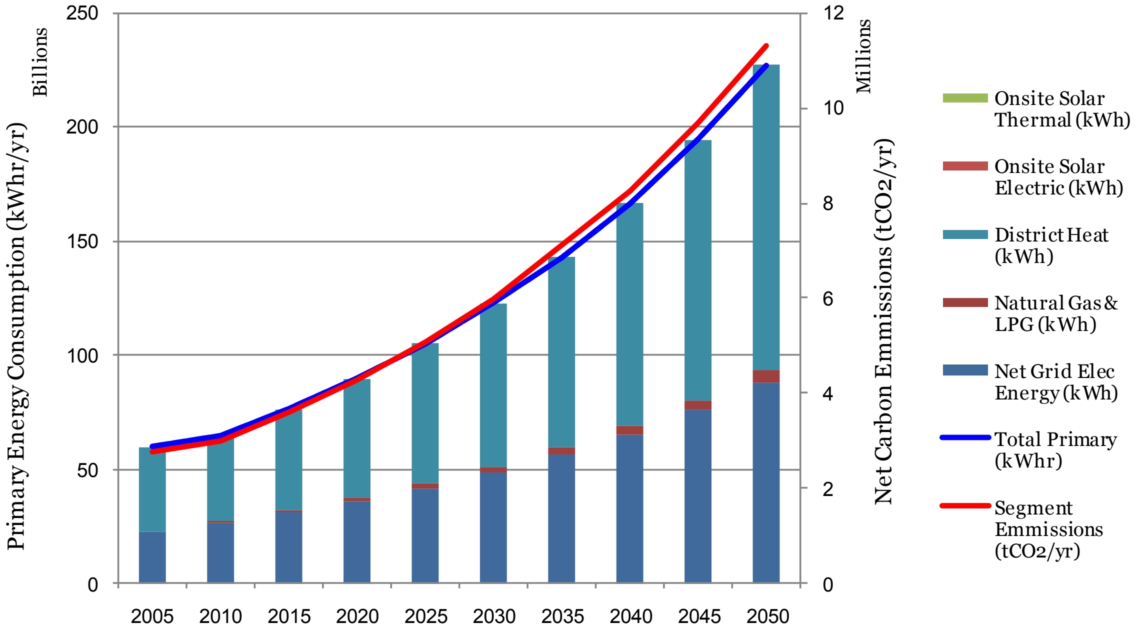

Figure 3- 9: Primary energy consumption and net carbon emissions for the entire multi-family segment according to baseline scenario 1 – Market response.

Illustrated in Figure 3-10 is the energy use per building, which experience in 2050 a 6% drop in consumption compared to 2005 levels. Between 2005 and 2010 the demand drops sensibly. This trend is visible in all scenario simulations (see next sections) and mainly depends on the fact that buildings, when possible, tend to adopt the ventilation system of reference segment 6 (construction year between 1981 and 1990), that, by assumption and differently from the others, has a heat-recovery system, allowing for consistent energy savings. In this perspective, a few actions are taken to optimise the HVAC system, only when refurbishment or construction of new buildings occurs. A slight increase in equipment efficiency is registered only when buildings are refurbished. No solar PV systems are installed.

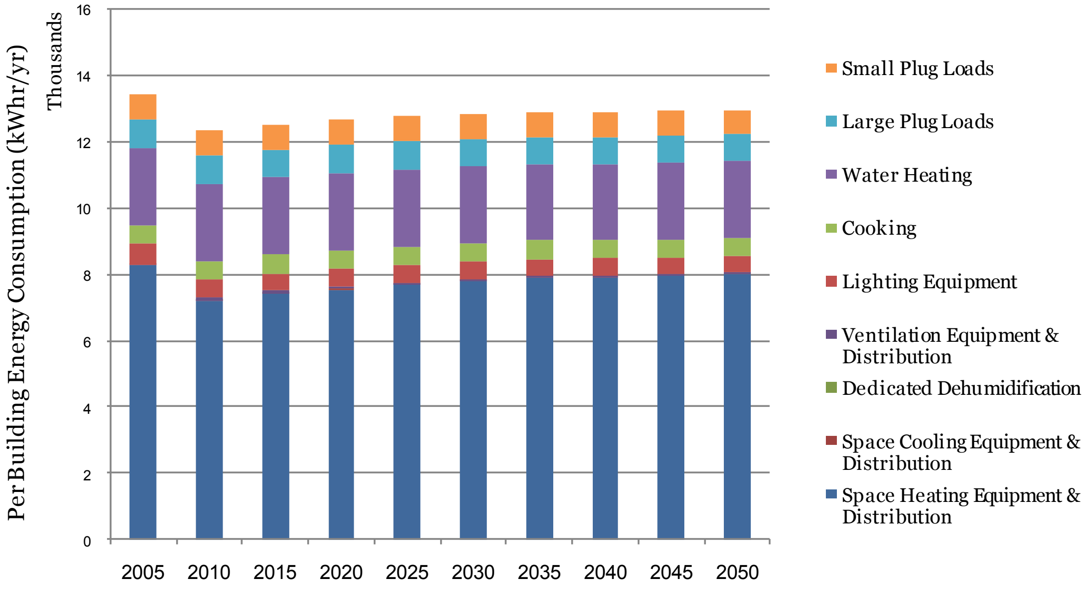

Figure 3- 10: Per building energy consumption according to baseline scenario 1 – Market response.

3.2.2 Baseline 2 – Current Swedish energy policy

This scenario intends to incorporate the economic instruments adopted by the Swedish government for improving energy efficiency in the residential sector. In year 2005 these were: (i) building regulations, (ii) 65% reduction in the investment cost for implementing solar PV and (iii) 35% cost reduction for converting the heating system. The assumption is that the measures are the same throughout the time range under analysis, i.e. until 2050. Figure 3-11 and 3-12 show the simulated primary energy consumptions of the multi-family stock and the average energy use for a single building.

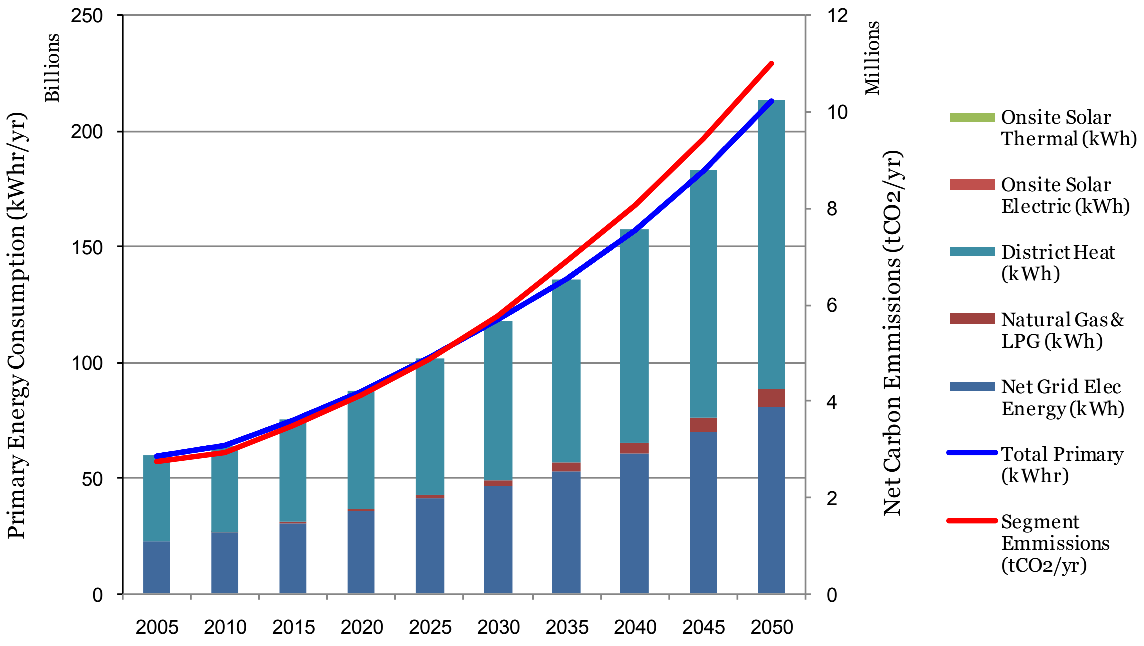

Figure 3- 11: Primary energy consumption and net carbon emissions for the entire multi-family segment according to baseline scenario 2 – Current Swedish energy policy.

Under baseline 2, the total energy consumption and the carbon emissions in 2050 register an increase of 357% and 400% compared to the 2005 values. On the contrary, building energy use decreases by 8% in respect to 2005 levels.

Compared to the business-as-usual case (baseline 1), current policies seem to achieve only a slight improvement in the multi-family stock (-2% on per-building energy use), and are still far from attaining a radical change in consumption and in carbon emission patterns in the multi-family residential sector.

In general, more efficient space heating and lighting equipment are adopted. Small and large plugs as well as cooking equipment are not much improved. Interestingly, although there are incentives for implementing solar PV technology, no such installation occurs.

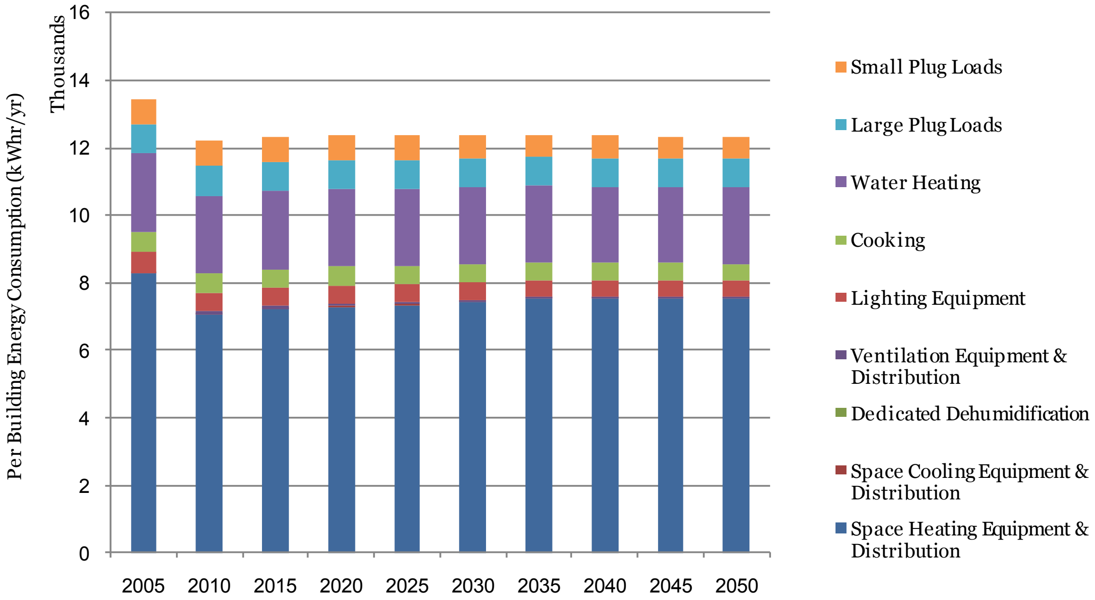

Figure 3- 12: Per building energy consumption according to baseline scenario 2 – Current Swedish energy policy.

3.2.3 Scenario 1 – Net Zero Energy Buildings (NZEB)

In order to simulate a zero net energy building, the EEB platform imposes specific constraints filtering out permutations that result in a positive net energy use. On the other hand, permutations that allow for zero or negative net consumption, meaning that the on-site energy generation is equal or higher than the energy demand, are considered suitable for the ZNE scenario.

In the EEB_Sweden v1.0 for multi-dwelling buildings, the only option that allows for on-site energy generation is the use of solar thermal (to heat DHW) and solar PV (to produce electricity, sold back to the grid).

However, in this study, even considering the most efficient systems, the energy gains by implementing both technologies are not enough to supply for the whole building energy demand. Therefore, it is not feasible to run this scenario since there are no possible permutations that meet the ZNEB requirements.

Solar irradiance in Sweden is on average lower than in most of the European countries. For instance, the yearly solar irradiance in Gothenburg (~1070 kWh/m^2) is more than 40% lower than in Marseille, south of France (~1800 kWh/m^2). (JRC, 2012)

Undoubtedly, the installation of solar thermal and solar panels contributes to improve energy efficiency in Swedish multi-family buildings but, at present, can hardly be enough to transform a building into a self-sustained shell. This conclusion diverge from the study on single- and two-family houses performed by Mundaca et al. (2011), where, according to the EEB simulations, a zero net energy building regulation for new constructions after 2020 is feasible and allows for a tangible efficiency improvement in the segment of single- and two-family houses.

However, two main considerations are worth to be mentioned: first, solar thermal and solar PV installed on a single or semi-detached house provide energy for one or maximum two households, while in a building, although the installed capacity is potentially higher, the energy gains have to be divided by the number of dwellings – e.g. 15 in the modelled baseline building in this work. Second, the energy data used in the single- and two-family segment model are average EU-15 values and therefore, according to what previously stated, it is likely that the on-site solar energy generation is overestimated. This is especially important to highlight since it stresses the importance of creating a database of energy performance values specifically for the country under analysis.

Furthermore, if the general trend of policies targeting the residential sector is to impose high restrictions on per-building energy use and lead the way towards the zero, or nearly-zero, net energy target, as already seen in the EU recast Directive on Energy Performance in Buildings (2010/31/EU), much more attention and support will have to be given to micro-scale renewable energy, including not only solar but also wind power potential.

3.2.4 Scenario 2 – 10x raise in energy prices

On the baseline of current energy policy (b2), this scenario introduces an energy price increase of a factor 10. Results are reported in Figure 3-13 and 3-14. This increase is introduced step-wise in the time range under analysis, so that the 10x rise is reached in 2050.

Primary consumption registers an increase of 356% compared to the 2005 level (Figure 3-15). In 2050 the energy use in buildings is reduced by 8% in relation to 2005 (Figure 3-16). Considering that in the baseline case (s2) the energy drop per building is estimated to be 8%, no net increase/decrease can be therefore attributed to the policy measure 10x raise in energy prices itself.

Results indicate that overall, decision-makers tend to avoid capital expenses for efficiency improvements in a time of pressing energy price increase. The scenario remains stagnant and no additional improvements are faced besides the actions taken under the baseline scenario b2.

On the basis of this outcome, it is possible to argue that gains in energy efficiency due to an increase in fuel price might be overestimated with modelling platforms that only take into account techno-economic aspects. This was also pointed out in the work by Mundaca et al. (2011) on single- and two-family houses.

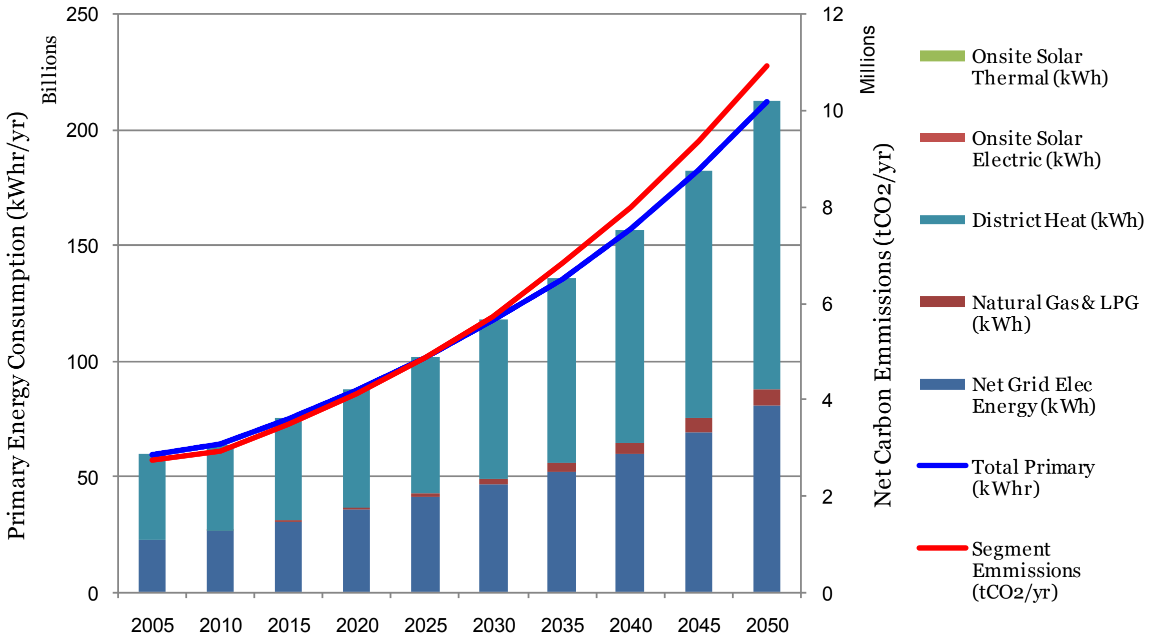

Figure 3- 13: Primary energy consumption and net carbon emissions for the entire multi-family segment according to policy scenario 4 – 10x raise in energy prices combined with current Swedish energy policy.

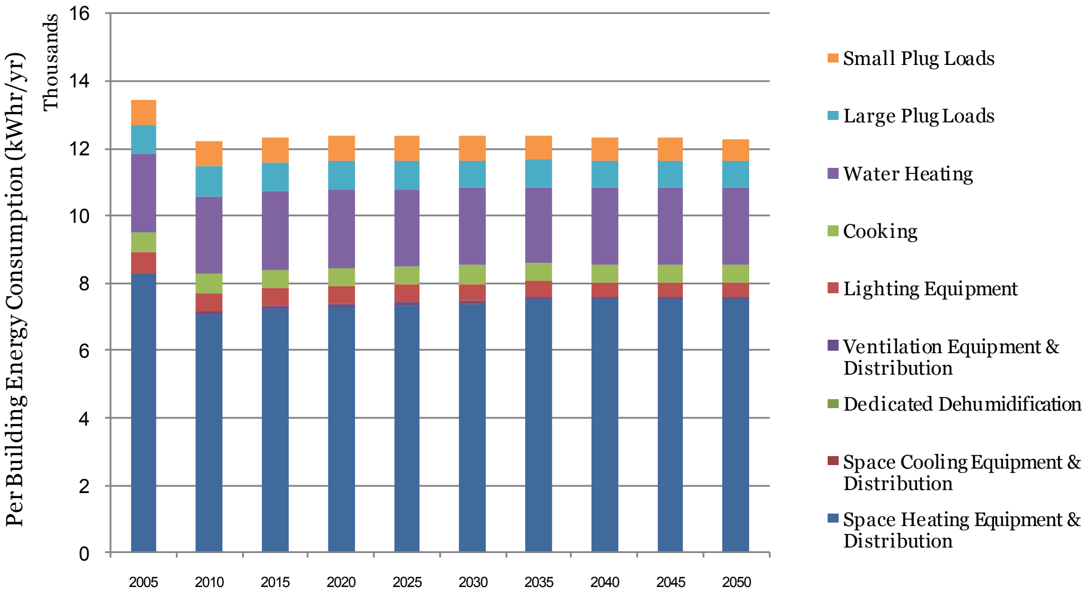

Figure 3- 14: Per building energy consumption according to policy scenario 4 – 10x raise in energy prices combined with current Swedish energy policy.

3.2.5 Scenario 3 – Financial incentives

This scenario reflects a situation where in addition to current energy policy (b2), economic incentives, in form of capital and labour cost reduction, are given when constructing new buildings that have a yearly energy consumption equal or below 90 kWh/m^2 (class A and B buildings, see Table 2-6).

The simulation results are shown in Figure 3-15 and 3-16.

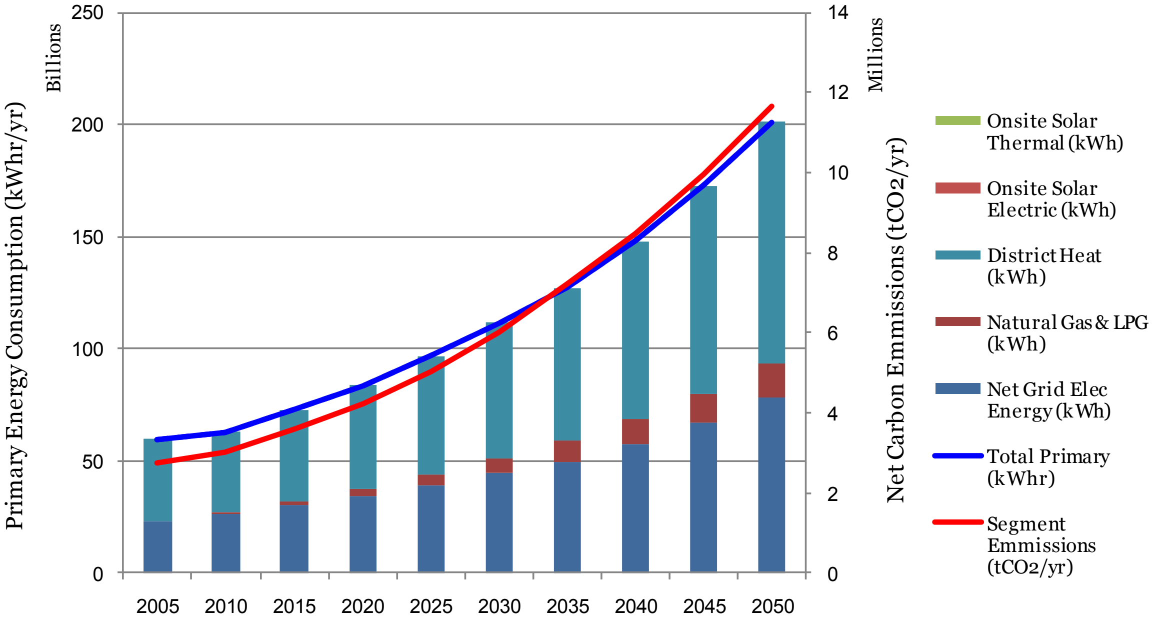

Figure 3- 15: Primary energy consumption and net carbon emissions for the entire multi-family segment according to policy scenario 5 – Incentives combined with current Swedish energy policy.

As illustrated in Figure 3-15, the primary energy consumption estimated for 2050 increases by 337% compared to 2005. Carbon emissions rise by 423% during the same time frame.

Single buildings in 2050 consume 11% less than in 2005 (Figure 3-16). Compared to the baseline scenario 2, the net decrease, attributed to the incentive measure, is 3%.

Figure 3- 16: Per building energy consumption according to policy scenario 5 – Incentives combined with current Swedish energy policy.

In this case, both solar thermal and solar PV are installed. However, the efficiency of household appliances (i.e. cooking equipment, large and small plugs) and lighting system is only slightly improved.

3.2.6 Scenario 4 – Carbon tax, bans and incentives

Scenario 4 aimed at simulating an extreme case, where carbon tax, bans, incentives and current energy policy are combined to study the response in the multi-dwelling building stock. Expected was a substantial decrease in building energy consumption.

As shown in Figure 3-17, primary energy use in 2050 increases by 231% in respect to the 2005 level. This value is sensibly lower than the baseline case outcomes, i.e. 357% for b2, emphasising the ability of this policy measure to materialise a delayed growth. However, carbon emissions augment by 463% mainly due to HVAC system change, from DH to natural-gas fuelled boiler.

The number of buildings not adopting any energy-efficient measures, the so-called fixed stock, is very small compared to the other scenarios. For instance, by year 2030, all household appliances (including cooking equipment, small and large plugs) and lighting systems consuming electricity are replaced by the most efficient technologies available in the model. It is possible to hypothesise that if more efficient technology packages (i.e. permutations) were to be present in the EEB platform, the per-building energy use would have experienced even more remarkable reductions by 2050.

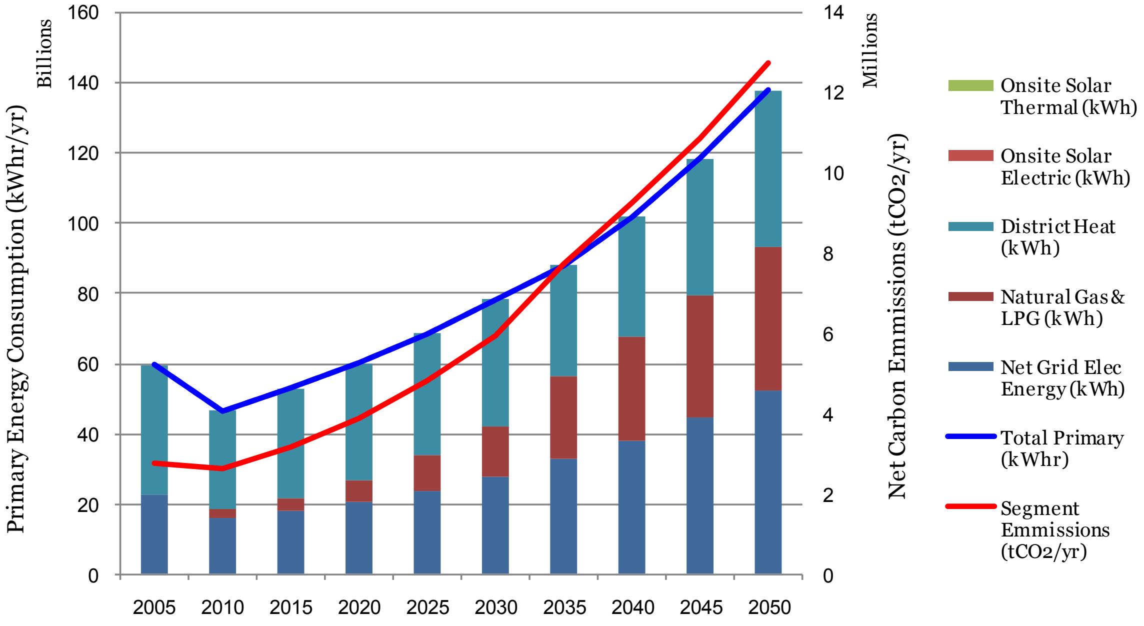

Figure 3- 17: Primary energy consumption and net carbon emissions for the entire multi-family segment according to policy scenario 6 – Carbon tax, bans and incentives combined with current Swedish energy policy.

Figure 3-18 Illustrates how the energy use per building changes between 2005 and 2050. During this time-span buildings become more efficient and use 27% less energy, due to improved HVAC technologies, efficient household appliances and lighting system, installation of solar thermal and solar PV.

It is interesting to compare these results with the outcome of Scenario 3 – Financial incentives. In this way it is possible to understand the weight of bans and taxes, which, according to these simulations, is very high: the per-building reduction in energy consumption passes from 11% (s3) to 27% (s4), thus observing a net improvement of 16% - to be attributed to the presence of carbon tax and bans.

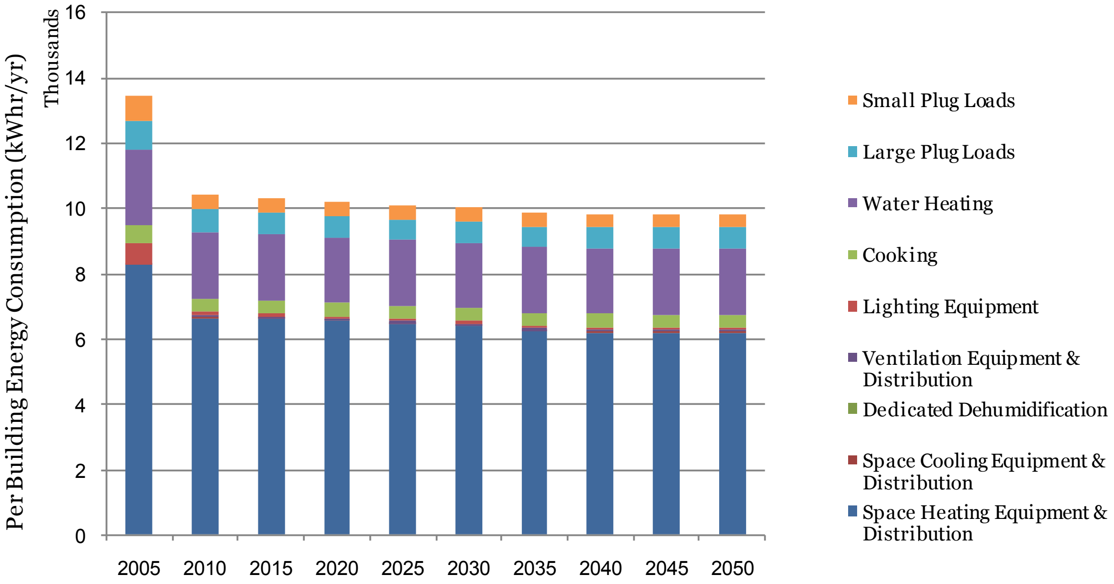

Figure 3- 18: Per building energy consumption according to policy scenario 6 – Carbon tax, bans and incentives combined with current Swedish energy policy.

3.2.7 Summary

The quantitative outcome of the policy analysis, in terms of increase or decrease in consumption levels, is reported and compared in Table 3-5.

Table 3- 5: Overview of primary energy growth and per-building energy reductions achieved by simulating different policies with the EEB_Sweden model. Values refer to multi-family buildings in Sweden, in year 2050 in respect to 2005.

	Primary energy use variation		**Building energy use variation**	
2050/2005	Simulation results	Without baseline	Simulation results	Without baseline
(b1) Market response	+380%		-6%	
(b2) Current Swedish energy policy	+357%		-8%	
(s1) 10x raise in energy prices + b2	+356%	+1%	-8%	±0%
(s3) Financial incentives + b2	+337%	-20%	-11%	-3%
(s4) Carbon tax, bans and incentives + b2	+231%	-126%	-27%	-19%

4 Conclusions

This thesis investigated present and future energy consumption in the Swedish multi-family residential sector by first creating comprehensive building models picturing the current stock, then analysing their energy performance and finally simulating the evolution of energy consumption and carbon emission patterns under different policy regimes, in the time range 2005-2050. The energy database was linked to the EEB_Sweden v.1.0 platform and several policy scenarios were simulated in order to analyse, ex-ante, the potential impacts of policy instruments that can shape future energy use in buildings and, even most important, which instruments have the power to transform (and to which level) consumption patterns in multi-family dwellings.

The energy performance of buildings representative of the Swedish multi-family stock was calculated using the simulator eQuest and considering 2005 as the baseline year. Results are consistent with statistical values: modelled energy consumption for DH and DHW differs from official data between 1% and 9% and a deviation of 14% is only reported for one segment (Ref 5). Values still remain within the default ± 15% margin of error to be attributed to results obtained with eQuest. Electricity consumption in households is on average slightly higher than statistical values. A feasible explanation is that modelled data incorporates electricity consumption from common areas in the building, which is neglected in official 2005 numbers. However, the general trend, observed in the last two reports on energy indicators by the Swedish Energy Agency (Energimyndigheten, 2011a, 2012a), is to include energy use from common areas and merge it with the households' consumption.

Sensitivity analyses were performed in order to assess the baseline building models degree of reliability. For this purpose, energy performance of buildings with different number of floors and associated to different weather files was carried out. Results suggest that deviations from baseline values can be neglected.

Besides providing estimates of the energy performance of the multi-family stock in 2005, energy values attributed to several technology packages reflecting future permutations in buildings were also calculated. For this purpose, baseline building models were implemented with energy-saving technologies (e.g. efficient HVAC equipments, thermostats, low energy lighting systems, efficient large and small plugs), on-site energy generation systems (solar thermal and solar PV), as well as different cooling systems, almost inexistent in multi-family buildings at present, but foreseen to play an increasing role in future energy consumption in Sweden.

The outcome was the creation of a comprehensive database of present and future energy values, specifically tailored for the Swedish multi-family residential sector.

Once the database was implemented in the EEB_Sweden platform, few test scenarios were simulated: two baseline cases, i.e. market response and current Swedish energy policy, and four additional policy scenarios, i.e. zero net energy buildings (ZNEB), 10x raise in energy prices, financial incentives and carbon tax, bans and incentives.

In general, it is possible to observe that major efficiency improvements are obtained by replacing ventilation system, increasing envelope and fenestration insulation, replacing heating system and improving lighting equipment. Differently from single and semi-detached houses, where the heating system is very diversified, all multi-dwelling buildings have by assumption district heating, which is quite efficient. The only possible change among the

EEB permutations consists in adopting, for heating purposes, a natural gas boiler, which consumes less but contributes to higher carbon emissions. This trend can be seen in all scenarios, with different extents. This is also the main reason why energy consumption is reduced at the expense of carbon emissions mitigation.

In particular, from the baseline case, current Swedish energy policy targeting the residential sector is not enough to result in tangible energy savings. Under this scenario, the improvement in the building energy use is 8%. To this absolute value a 6% has to be subtracted, since this represents the degree of improvement that would occur in the situation of business-as-usual, i.e. when no policy instruments are applied.

Moreover, a ZNEB scenario is not feasible in this work. In fact, modelled energy values do not allow for buildings with yearly zero-net energy consumption. This is in disagreement with the EEB analysis on single and semi-detached houses performed by Mundaca and Neij (2011), where average EU-15 data was used to picture the Swedish residential sector. Results also show that at present on-site energy generation from solar thermal and solar PV is not enough to balance out consumption in buildings. In order to reach the ZNEB target, these technologies have to be combined with radical improvements in envelope and fenestration isolation as well as in HVAC efficiency. For this purpose, technology packages incorporated in the EEB_Sweden platform need to be updated and eventually implemented in order to understand whether ZNE buildings are at all feasible in a cost-benefit perspective. If zero or nearly-zero net energy will be set as goal for future new buildings, more aggressive policy instruments for micro-scale energy generation are strongly needed.

Furthermore, a 10x raise in energy prices seem to trigger a slowdown in adopting more efficient technologies, as also reported in the single- and two-family houses analysis. Energy use in buildings in 2050 remains unchanged compared to 2005. Decision-makers' non-rational behaviour seems to strongly affect the outcome and individuals are not inclined to face capital expenses for new technologies although the replacement would allow them savings in the longer run

On the other hand, average energy gains are reported if incentives for constructing low consumption buildings, combined with current energy policy, are granted. A 11% drop in per-building energy use is simulated, thus reflecting a net decrease of 3% to be attributed to the role of the incentives.

Finally, a critical decrease in energy consumption is obtained by imposing carbon taxes, construction incentives and bans, thus proving that more integrated policy instruments have the potential to trigger a radical transformation in the multi-family sector. In detail, in scenario 4, per building energy consumption in 2050 diminish by 27% compared to 2005 levels. It is worth mentioning that a more rational behaviour amongst decision-makers is triggered, e.g. electricity driven appliances in households are very quickly replaced by more efficient elements.

At this point, it is important to highlight that the current study in not free from uncertainties and limitations, and that data gaps were replaced by assumptions. Therefore, under this perspective, results have to be considered with appropriate caution.

The uncertainties of the modelling outcomes could be reduced by further developing this work. For this purpose, the enlargement of the permutation portfolio in the EEB_Sweden model for multi-dwelling buildings is a priority. Current available technologies should be better represented in the platform, enabling more reliable evolutions of policy scenarios. Moreover, updated specific cost values (e.g. prices for technologies, labour and maintenance costs) retrieved directly from the current Swedish market, e.g. from vendors, carpenters and construction companies, should be inserted in order to increase the level of confidence. Furthermore, taking advantage of one of the strongest features of the EEB platform, an investigation of the role of non-financial aspects is also suggested. Such analysis was partially carried out during this work, and preliminary results shows that a better understanding of decision-makers' behaviour under different circumstances, e.g. more or less integrated policy scenarios, would allow policy makers to improve and shape policy instruments in favour of a more sustainable development.

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Appendix A

Example of a baseline technology configuration and permutation packages (reference segment 5) reported in the "Energy db" segment of the model EEB_Sweden for multi-family dwelling buildings.

Baseline configuration:
Ref5: triple pane windows, R-3.3 wall insul, R-5.5 roof insulation, DH, CFL, DH for H2O, efficient small plugs

Technology permutations:
Ref5:2 + Imp Wall+Roof
Ref5:3 + Super Wall +Roof
Ref5:4 + Imp Window
Ref5:5 + Super Window
Ref5:6 + CFL Lighting
Ref5:7 + LED Lighting
Ref5:8 + OccSensor
Ref5:9 + HELgApp
Ref5:10 + Imp Ctrl -Thermostat ctrl for BB
Ref5:11 + HE HVAC
Ref5:12 + GTHP HVAC
Ref5:13 + HE PLANT-Elec
Ref5:14 + HE Plant-Abs
Ref5:15 + HE Boiler
Ref5:16 + HEWaterheater
Ref5:17 + Solar thermal
Ref5:18 + HEWaterheater+Sol Th
Ref5:19 + Imp Envelope
Ref5:20 + Super Envelope
Ref5:21 + HE Internal loads
Ref5:22 + Imp Env+HE IntLds
Ref5:23 + Imp Env+HE IntLds+HE WH
Ref5:24 + Imp Env+HE IntLds+HE WH+Sol th
Ref5:25 + Imp Env+HE IntLds+Imp Ctrl
Ref5:26 + Imp Env+HE IntLds+HE HVAC
Ref5:27 + Imp Env+HE IntLds+GTHP HVAC
Ref5:28 + Imp Env+HE IntLds+HE E_PLANT
Ref5:29 + Imp Env+HE IntLds+HE Ab_PLANT
Ref5:30 + Imp Env+HE IntLds+HE Boiler
Ref5:31 + Imp Env+HE IntLds+HE WH +Imp Ctrl
Ref5:32 + Imp Env+HE IntLds+HE WH + Imp Ctrl + HE HVAC
Ref5:33 + Imp Env+HE int lds+HE WH + Imp Ctrl + GTHP
Ref5:34 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT
Ref5:35 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT
Ref5:36 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Boiler
Ref5:37 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + HE Boiler
Ref5:38 + Imp Env+HE int lds+HE WH + Imp Ctrl + GTHP + HE Boiler
Ref5:39 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE E_Plant + HE Boiler
Ref5:40 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_Plant + HE Boiler
Ref5:41 + Sp Env+HE IntLds
Ref5:42 + Sp Env+HE IntLds+HE WH
Ref5:43 + Sp Env+HE IntLds+Imp Ctrl
Ref5:44 + Sp Env+HE IntLds+HE HVAC
Ref5:45 + Sp Env+HE IntLds+GTHP HVAC
Ref5:46 + Sp Env+HE IntLds + Imp Ctrl + HE E_PLANT
Ref5:47 + Sp Env+HE IntLds + Imp Ctrl + HE Abs_PLANT
Ref5:48 + Sp Env+HE IntLds+HE Boiler
Ref5:49 + Sp Env+HE IntLds+HE WH +Imp Ctrl
Ref5:50 + Sp Env+HE IntLds+HE WH + Imp Ctrl + HE HVAC

Ref5:51 + Sp Env+HE int lds+HE WH + Imp Ctrl + GTHP
Ref5:52 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT
Ref5:53 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT
Ref5:54 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Boiler
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Ref5:67 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE E_Plant + HE Boiler + Sol th
Ref5:68 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_Plant + HE Boiler + Sol th
Ref5:69 + Sp Env+HE int lds+HE WH + Imp Ctrl+ Sol th
Ref5:70 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + Sol th
Ref5:71 + Sp Env+HE int lds+HE WH + Imp Ctrl + GTHP + Sol th
Ref5:72 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT + Sol th
Ref5:73 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT + Sol th
Ref5:74 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Boiler + Sol th
Ref5:75 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + HE Boiler + Sol th
Ref5:76 + Sp Env+HE int lds+HE WH + Imp Ctrl + GTHP + HE Boiler + Sol th
Ref5:77 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT + HE Boiler + Sol th
Ref5:78 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT + HE Boiler + Sol th
Ref5:79 + Imp Env+HE int lds+HE WH + Imp Ctrl + Sol th +PV
Ref5:80 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + Sol th +PV
Ref5:81 + Imp Env+HE int lds+HE WH + Imp Ctrl + GTHP + Sol th +PV
Ref5:82 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT + Sol th +PV
Ref5:83 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT + Sol th +PV
Ref5:84 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Boiler + Sol th +PV
Ref5:85 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + HE Boiler + Sol th +PV
Ref5:86 + Imp Env+HE int lds+HE WH + Imp Ctrl + GTHP + HE Boiler + Sol th +PV
Ref5:87 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE E_Plant + HE Boiler + Sol th +PV
Ref5:88 + Imp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_Plant + HE Boiler + Sol th +PV
Ref5:89 + Sp Env+HE int lds+HE WH + Imp Ctrl+ Sol th +PV
Ref5:90 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + Sol th +PV
Ref5:91 + Sp Env+HE int lds+HE WH + Imp Ctrl + GTHP + Sol th +PV
Ref5:92 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT + Sol th +PV
Ref5:93 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT + Sol th +PV
Ref5:94 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Boiler + Sol th +PV
Ref5:95 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE HVAC + HE Boiler + Sol th +PV
Ref5:96 + Sp Env+HE int lds+HE WH + Imp Ctrl + GTHP + HE Boiler + Sol th +PV
Ref5:97 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE E_PLANT + HE Boiler + Sol th +PV
Ref5:98 + Sp Env+HE int lds+HE WH + Imp Ctrl + HE Abs_PLANT + HE Boiler + Sol th +PV