Philipp Weiss

Simple Question, Complex Answer

*Pathways Towards a 50% Decrease in Building Energy Use*

Licentiate Thesis
Abstract


Addressing building energy use is a pressing issue for building sector decision makers across Europe. In Sweden, some regions have adopted a target of reducing energy use in buildings by 50% until 2050. However, building codes currently do not support as ambitious objectives as these, and novel approaches to addressing energy use in buildings from a regional perspective are called for. The purpose of this licentiate thesis was to provide a deeper understanding of most relevant issues with regard to energy use in buildings from a broad perspective and to suggest pathways towards reaching the long-term savings objective. Current trends in building sector structure and energy use point to detached houses constructed before 1981 playing a key role in the energy transition, especially in the rural areas of Sweden. In the Swedish county of Dalarna, which was used as a study area in this thesis, these houses account for almost 70% of the residential heating demand. Building energy simulations of eight sample houses from county show that there is considerable techno-economic potential for energy savings in these houses, but not quite enough to reach the 50% savings objective. Two case studies from rural Sweden show that savings well beyond 50% are achievable, both when access to capital and use of high technology are granted and when they are not. However, on a broader scale both direct and indirect rebound effects will have to be expected, which calls for more refined approaches to energy savings. Furthermore, research has shown that the techno-economic potential is in fact never realised, not even in the most well-designed intervention programmes, due to the inherent complexity of human behaviour with respect to energy use. This is not taken account of in neither current nor previous Swedish energy use legislation. Therefore an approach that considers the technical prerequisites, economic aspects and the perspective of the many home owners, based on Community-Based Social Marketing methodology, is suggested as a way forward towards reaching the energy savings target.

Keywords: Buildings, Regional energy policy, Energy efficiency, Rebound effect, Community-Based Social Marketing

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# Abbreviations

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<th>Description</th>
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<tbody>
<tr>
<td>ACH</td>
<td>Air Changes per Hour</td>
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<tr>
<td>ANF</td>
<td>Annuity Factor</td>
</tr>
<tr>
<td>CBSM</td>
<td>Community-Based Social Marketing</td>
</tr>
<tr>
<td>CFL</td>
<td>Compact Fluorescent Light</td>
</tr>
<tr>
<td>CGE</td>
<td>Computable General Equilibrium</td>
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<tr>
<td>EPC</td>
<td>Energy Performance Certificate</td>
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<tr>
<td>EPS</td>
<td>Extruded Polystyrene</td>
</tr>
<tr>
<td>EPSG</td>
<td>Extruded Polystyrene with Graphite Content</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>GHG</td>
<td>Greenhouse Gases</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<td>LED</td>
<td>Light-emitting Diode</td>
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<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>NUTS</td>
<td>Nomenclature des Unités Territoriales Statistiques</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>RAER</td>
<td>Reasonably Achievable Emissions Reductions</td>
</tr>
<tr>
<td>RAES</td>
<td>Reasonably Achievable Energy Savings</td>
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<tr>
<td>SCB</td>
<td>Statistics Sweden</td>
</tr>
<tr>
<td>SHGC</td>
<td>Solar Heat Gain Coefficient</td>
</tr>
<tr>
<td>SMHI</td>
<td>Swedish Meteorological and Hydrological Institute</td>
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Use of Currencies

All currency values are given in Euros (EUR). In many cases, the original economic calculations are based on values in Swedish kronor (SEK). The conversion rate used throughout the thesis is $1 \text{ EUR} = 9 \text{ SEK}$. 
Preface

This licentiate thesis would not have been written had there not been a meeting held with a group of actors within the building sector in the Swedish county of Dalarna in early 2009. The topic for the meeting was the national objective of a 50% reduction in energy use in buildings until 2050. The simple question the group asked themselves was: How can this be achieved in our county? They soon realised that answering this question would require further research. A project was initiated in late 2009, which turned into a PhD project in early 2010 and quickly many more questions were raised. Some of these will be answered in this licentiate thesis and my hope is that it will create a solid foundation for further inquiries of how building energy use can be dealt with from a regional perspective, using insights from the national and even global perspective for a well-informed decision making process.

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Stjärnsund

December 2013.
1. Introduction

Already now the impact of human activities on the life support systems on Earth have in several areas by far exceeded sustainable levels (see for instance [1]), which has raised serious concerns an eventual collapse of human civilisation [2]. All of the human enterprise needs to be re-evaluated and re-aligned to a more harmonious relation to the natural systems, and housing plays a major role in that undertaking, given that energy use in buildings accounts for large environmental impacts from the extraction of energy carriers for electricity production all the way to fuel combustion in the buildings themselves. In the European Union, energy use in buildings accounts for roughly 40% of total energy use and the sector is responsible for 36% of the CO$_2$ emissions in the EU [3]. Therefore, the long-term objective of reaching a 80-95% reduction in greenhouse gas emissions by 2050 [4] cannot be reached without addressing the buildings sector. The residential and services sector is also the sector that is expected to contribute most to the 2050 objective, second only to the power sector [4].

Furthermore, there are concerns about energy security of supply that call for a decrease in fuel dependency from countries outside the EU, as import dependency is already as high as 60% for gas and 80% for oil [5] and is likely to increase as domestic sources continue to dwindle. Finally, energy costs are a major expense especially in the residential part of the building sector and energy costs have been on the rise for years. Average EU-27 electricity prices for household consumption (including all taxes) for example rose by 25% between 2007 and 2012 [6]. Ever rising fuel prices have raised concerns for increasing “fuel poverty” that already is a reality for one in seven households in the EU [7] and which leads to serious health risks for the occupants, due to worsened indoor climate.

In Sweden, the situation is somewhat different. Energy use in buildings accounts for 40% of final energy use here, too [8], but only roughly 6% of total CO$_2$ emissions occur in the building sector [9]. Most of the energy used in buildings is produced from domestic sources [8], and security of energy supply is therefore not a prioritised topic for this sector. Even though energy prices have been on the rise in Sweden as well (electricity prices increased by 29% between 2007 and 2012 [6]), energy poverty is not yet regarded a problem in the country. However, some building sector actors fear that this might change in the light of new EU regulation [10]. Nevertheless, the reduction of energy use has been a top priority in Sweden, and a 50%
A reduction in energy use by 2050 was until recently a national environmental objective (see Chapter 2). In recent years, the sector has received renewed attention due to the fact that 75% of the Swedish housing stock will have to undergo refurbishment until 2050 [11], which represents an opportunity for achieving energy savings.

In the light of these challenges, the aim of this licentiate thesis is to provide a solid background on both challenges and opportunities with regard to energy use in the building sector and to suggest possible pathways towards a substantially lower energy use in buildings. The approach chosen is interdisciplinary, with the objective of providing a broad picture of the aspects that will be relevant for future work on energy use in buildings. The width of this thesis naturally comes at the expense of the level of detail in the different chapters and the work presented here will have to be complemented by in-depth analyses.

Regarding scope, the thesis focuses primarily on the Swedish building sector and the county of Dalarna is used as study area in several parts of the thesis. The county has a total population of 276,000 inhabitants and an area of 31,000 km², which is roughly the same size as Belgium. The county has 15 municipalities, of which Falun and Borlänge are the largest, with a total population of roughly 100,000 people. The annual average temperature was approximately 4.5°C during the period of 1961 to 1990, placing the county in one of the colder parts of Europe, comparable to off-coast Finland or Western Russia. The county was chosen as a study area for several reasons. For one thing, it is representative of many other Swedish regions with non-metropolitan characteristics as regards population, population density, average household income, real estate prices and building stock structure. As we will see in Chapter 4, these parts of Sweden deserve special attention, since they have been experiencing relative neglect from the authorities with regard to building energy use, despite the fact that roughly 60% of the Swedish population live in parts of the country with similar characteristics.

Furthermore, the county has been pioneering work with building sector energy use in Sweden, both through an active stakeholder network called the “Building Dialogue” and through an ambitious County Administrative Board, whose work has produced some of the most ambitious energy savings objectives in the country. The high level of expertise and interest for energy use in buildings in the county allowed for close contact and continuous knowledge exchange during the work on this thesis (see Chapter 8 for further details).

The thesis is structured along three main themes, see Figure 1. The first theme provides background information and establishes the statistical base that is used in the second theme on simulations and case studies. In the third theme layers of complexity are added and barriers and limitations of the findings from the first two themes are explored.
The thesis is divided into nine chapters. Chapter 2 gives an overview of EU regulation affecting energy use in buildings, long-term energy savings objectives as well as Swedish legal requirements and steering instruments on energy use in buildings relevant for the context of this thesis. Chapter 3 reviews the criticism put forward against efforts to increase energy efficiency in general and discusses the rebound effect and its implications on building energy use, as well as how the rebound effect dilemma could be solved. Chapter 4 presents findings for the structure and energy use as well as potential future development of the building sector in Dalarna and compares these to characteristics for the national level. These findings form the basis for Chapter 5, in which the potential for energy savings in detached houses in Dalarna is investigated through the simulation of the implementation of energy savings measures in eight different sample houses. Chapter 6 then presents case studies of two Swedish houses where energy savings beyond 50% are achieved with altogether different strategies. Chapter 7 gives an outlook on how behavioural aspects make saving energy in buildings more complicated and how these aspects can be dealt with. The overall findings from this licentiate thesis and their implications for future research are discussed in Chapter 8. From these, conclusions are drawn in Chapter 9.
2. Objectives, EU Regulation and Legal Requirements on Energy Efficiency in Buildings

2.1 Introduction

As in many other countries, energy efficiency has been a part of building sector regulation since the mid 1970’s in Sweden, due to the energy shortages imposed by the first oil crisis in 1973. Generally speaking, influence on the energy performance of residential buildings (and their users) has been taken using building codes, energy performance certificates, taxes, investment grants, information and education (including energy advisors and energy labelling). In recent years, these activities have been highly influenced by EU policy, especially through the Directive 2010/31/EC of the European Parliament and of the Council on the energy performance of buildings (EPBD) [12], Directive 2012/27/EU of the European Parliament and of the Council on Energy Efficiency [13] as well as the recast of Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy related products [14].

2.2 European Regulation

Through the EPBD, which is the directive with most influence on the building sector, member states are required to set minimum energy performance standards for both existing and new buildings. By 31 December 2020 (2018 for buildings occupied and owned by public authorities) all new buildings must be nearly zero-energy consumption buildings. Existing buildings must comply with the same requirements when they undergo major renovations (to be defined by each member state), but there is a possibility to exempt from the minimum requirements officially protected buildings, buildings used as places of worship, temporary buildings, residential buildings intended for a limited annual time of use and stand-alone buildings with a total useful floor area of less than 50 m². Furthermore, the energy used in buildings should be “covered to a very significant extent
by energy from renewable sources, including energy from renewable sources produced on-site or nearby.” (Art. 2.2).

2.3 Swedish Energy Objectives

In Sweden, energy efficiency in buildings was until recently a top-priority and was addressed through a national environmental objective that called for a 50% reduction in energy use in buildings by 2050, with an intermediate objective of a 20% reduction until 2020. The base year for the objectives was 1995 [15]. The objective was not specified further. In the original government bill from 2005 [16] the objective was intended to be evaluated on a regular basis based on primary energy factors. This was not included in the eventual formulation of the objective and no clarification as to what was really meant by the objective had been provided by the government prior to the removal of the objective in 2012. However, the widespread interpretation had been that the objective addresses specific energy use for heating and hot water per m². There were also regionalised environmental objectives for each of the Swedish counties. For the case of Dalarna a 50% decrease until 2050 was aimed for, with intermediate objectives of 10% until 2010 and 30% until 2025. The base year for the regionalised objectives was 2000.

The removal of the energy savings objective was surrounded by some controversy, as it had been widely recognised as a guiding objective in long-term building sector planning. The associated policy document [17] did not help to clarify why the objective was removed. It simply states that “deletion of the former objective does not mean that the objectives for energy use in buildings have been changed as such” (author’s translation). The county administrative boards, who represent the Swedish state in the regions and to whom much of the responsibility for the policy-related work with the energy savings target had been delegated, are, however, willing to carry on with the work they have begun despite the current lack of clarity related to the objectives. The county of Dalarna aims to reduce energy use in buildings by 25% until 2020 and by 50% until 2050, using 2005 as a base year. Interestingly, the reduction objectives are formulated in absolute terms and including all energy use in buildings (even household electricity use). These new objectives also replace the regionalised environmental objectives that had been valid until 2012 [18].
2.4 Building Codes in Sweden

Building energy use is addressed directly from a legislation perspective solely through the national buildings codes. Swedish building codes have been subject to a number of changes in the past years, with the most significant one being a shift in 2005 from a required U-value for the entire building to an energy performance requirement in kWh/m$^2$, year, the value of which is dependent on the climate zone in which the building is located [19]. The requirements set in the EPBD were addressed in a Government written communication stating that nearly zero-energy buildings are buildings that have a better energy performance than current building codes [20]. The Swedish building codes were revised in 2013, partly as a response to the requirements set in the EPBD. Energy use requirements for new houses differ between the three climate zones in Sweden\(^1\) and depend on whether or not electricity is used as the main energy carrier for heating, see Tables 1 and 2 below. The building codes set requirements for both specific energy use expressed in kWh/m$^2$ heated space area and the average U-value for the building. For electrically heated houses, a limit to the installed electric power is set, too. Energy use requirements only include final (purchased) energy use for heating, hot water and ventilation. Electricity and heat produced (and consumed) on-site from solar collectors and solar photovoltaics (PV) is interestingly not included in the energy use of a building, nor is heat used by a heat pump. Household electricity is not included either and primary energy use is not addressed directly. The reason why electric energy use is now addressed separately is that the use of electricity-driven heat pumps for space heating is very common in Sweden. Before the introduction of special codes for electricity-heated houses, buildings equipped with heat pumps were largely favoured by the legislation, since no primary energy perspective was used. The Swedish Energy Agency estimates that almost half of all detached houses in Sweden (923,000) are equipped with some kind of heat pump. More than half of the heat pumps installed are of air/air type [21].

*Table 1: Final energy use requirements for heating of residential buildings not heated with electricity [22].*

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy use (kWh per m$^2$ $A_{\text{temp}}$, year)</td>
<td>130</td>
<td>110</td>
<td>90</td>
</tr>
<tr>
<td>Average U-value (W/m$^2$ K)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
</tbody>
</table>

\(^1\) Climate zone 1: Counties of Norbotten, Västerbotten and Jämtland. Climate zone 2: Counties of Västernorrland, Gävleborg, Dalarna and Värmland län. Climate zone 3: All remaining counties.
Table 2: Final energy use requirements for heating of residential buildings with electric heating [22].

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy use (kWh per m² A&lt;sub&gt;temp&lt;/sub&gt;, year)</td>
<td>95</td>
<td>75</td>
<td>55</td>
</tr>
<tr>
<td>Installed electric power for heating (kW)</td>
<td>5.5</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td>+ addition when A&lt;sub&gt;temp&lt;/sub&gt; is larger than 130 m²</td>
<td>0.035(A&lt;sub&gt;temp&lt;/sub&gt; – 130)</td>
<td>0.030(A&lt;sub&gt;temp&lt;/sub&gt; – 130)</td>
<td>0.025(A&lt;sub&gt;temp&lt;/sub&gt; – 130)</td>
</tr>
<tr>
<td>Average U-value (W/m² K)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
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</table>

The figures laid out in the building codes can be compared to current energy use in buildings. Detached houses for example use on average 116.9 (± 2.8) kWh/m² for heating and hot water, with houses constructed before 1941 using 139 (±6.6) kWh/m² and houses constructed after 2001 using 95.6 (±8.9) kWh/m². Houses that are heated with electricity exclusively use on average 98 (±4) kWh/m², with houses constructed before 1941 using 119 (±15) kWh/m² and houses constructed after 2001 using 86 kWh/m² [21].

Nässén and Holmberg [23] attempted to quantify the effect of building codes vs. other intervention instruments. They show that the heating demand in the Swedish building stock decreased from approximately 340 kWh/m², year to 180 kWh/m², year between 1970 and 2000. About 40% of this change was attributed to the lower energy demands in new buildings, the remaining improvement was due to improvements in the existing building stock. The effect of single intervention instruments, however, was not isolated from the data, and a more thorough analysis of the effectiveness of building codes as a steering instrument remains to be made. Although Nässén and Holmberg [23] do not mention this, much of the savings in existing buildings were probably achieved by the above mentioned widespread installation of heat pumps.

Regarding building refurbishment, the building codes state that energy efficiency must not be lowered after refurbishments, unless the requirements presented in Tables 1 and 2 are still fulfilled, although no mention is made of how these codes are intended to be enforced. If these values are not fulfilled, certain U-values for different building components should be achieved, see Table 3. However, the Swedish Planning and Building Act, PBL [24], states that alterations to all buildings must be made cautiously and with respect for the historical, cultural, environmental and artistic characteristics of the building (Chapter 8, §17). For instance, the exterior of some buildings may not be altered when improving the energy performance of the building, which limits the variety of measures that can be used and may be reason enough to become exempt from the energy use requirements. The rules set
out in the PBL deserve particular attention in the context of energy efficiency in rural regions, where the proportion of historic buildings (constructed before 1941) is often higher than the national average.

Table 3: Required minimum U-values after refurbishment.

<table>
<thead>
<tr>
<th>$U_i$</th>
<th>[W/m²,K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{roof}}$</td>
<td>0.13</td>
</tr>
<tr>
<td>$U_{\text{wall}}$</td>
<td>0.18</td>
</tr>
<tr>
<td>$U_{\text{floor}}$</td>
<td>0.15</td>
</tr>
<tr>
<td>$U_{\text{window}}$</td>
<td>1.2</td>
</tr>
<tr>
<td>$U_{\text{door}}$</td>
<td>1.2</td>
</tr>
</tbody>
</table>

2.5 Other Regulatory Instruments

In addition to building codes, energy use in buildings in Sweden has been influenced from a regulatory perspective by energy performance certificates, taxes, investment grants, information and education.

Energy performance certificates are one of the key tools devised in the EPBD to improving the energy performance of buildings. Energy performance certificates have been compulsory for most multi-family houses and non-residential premises since 1 January 2009, but to date (September 2013) only 58% of these buildings have an energy performance certificate [25]. Furthermore, privately owned one- and two dwelling houses are required to have an energy performance certificate established when they are sold, but no detailed statistics are available on the implementation rate of this type of certification for the national level. For the case of Dalarna, 7% of the detached houses are certified (see Chapter 4 for details). Several evaluations of energy performance certificates indicate that they are not effective as a means to promote energy efficiency improvements. The Danish Energy Agency found energy performance certificates to be the most expensive energy efficiency measure, being more than 15 times more expensive per saved kWh than other energy efficiency measures [26]. A German study found that energy performance certificates are of minor importance for purchase decisions and that utility bills are more important for assessing the energy performance of the dwelling than the certificate [27]. A study by the European Commission on the effect of energy performance certificates on housing prices in nine different locations found, however, that better energy performance has some effect on housing market prices [28].

Taxes on energy use have had a positive effect on energy efficiency, but need to be complemented by other instruments [19], as their effectiveness is
limited and can sometimes even have a crippling effect on energy efficiency, as they for low-income groups in particular may make it impossible to undertake investments into energy efficiency [29]. The use of usually time-limited grants for energy performance improvements in residential buildings has a long tradition in Sweden. Recent examples include grants for the installation of energy efficient windows, the conversion of detached houses with electric resistance heating and a grant for the installation of solar cells. No evaluation of the effectiveness of these grants has been made by the authorities [19].

Energy efficiency information is being provided by the Swedish Energy Agency, the Environmental Protection Agency and nowadays also by the Swedish National Board of Housing, Building and Planning. The permanent information activities have been complemented with special campaigns, but no evaluation has been made of the effectiveness of information measures either [19]. Another element of Swedish energy efficiency instruments is the use of local energy advisors to raise energy awareness primarily in households. Their efforts have been evaluated in several studies, but the actual impact of the programme is highly uncertain as very few people actually use the services of the energy advisors [19]. A third cornerstone when it comes to information is the use of energy labels as required by EU legislation. McCormick and Neij [19] report that these have had a huge effect on the average energy use for new appliances, but they ignore that these gains are likely to have been at least offset by an increase in the number of appliances per household, as illustrated by Gram Hansen [30] for the Danish case, see Figures 2 and 3 below. This is also the main explanation behind the 58% increase in household energy use in Swedish detached houses (from 3,800 to 6,000 kWh per year) that was observed during the period 1970 to 2011 [21].

Figure 2: Energy use of different household appliances from 1980 to 2004 in kWh per year (from [30]).
2.6 Discussion and Conclusions

The realm of building energy regulation in Sweden is constantly evolving, with EU regulation gaining more and more influence. On the national level, building codes and the now removed environmental objective on reduced energy use in buildings are set in specific terms, i.e. in kWh per m². This is problematic, since a reduction in specific energy use does not guarantee a reduction in overall energy use. For what is the use of lower specific energy use, if new houses become bigger and bigger and if the heated space area per occupant becomes ever larger\(^2\), as has been the case in Sweden the past 25 to 30 years? Furthermore, the objectives incorporate neither household electricity use nor a primary energy perspective. This is problematic, too, since household electricity use has been increasing drastically over the past four decades and will form an ever larger share of total building energy use as the heating loads decrease. The lack of a primary energy perspective finally poses the risk of favouring sub-optimal savings measures in the buildings, since effects higher up in the value chain are not taken into account. The dissemination of heat pumps (especially air-sourced ones) would surely not have been as massive had primary energy use played a role.

The county of Dalarna is thus closer to the right track and displays a substantially higher level of ambition with regard to the long-term energy savings objective, although no primary energy perspective is chosen here, either. On the one hand the objective is set in absolute terms, on the other hand 2005 is chosen as a base year, which thereby excludes the savings

\(^2\) The average heated floor area of detached houses increased from 139 m² for houses constructed between 1981 and 1990 to 154 m² for houses constructed after 2001 [21]. Furthermore, the number of occupants per dwelling in Sweden decreased from 1.99 in 1990 to 1.93 in 2008 (calculated from [31] and [32]).
already achieved between 1995 (the base-year for the former national objective) and 2005.

While the use of intermediate targets is appropriate in many contexts, especially GHG emission targets, this is not necessarily the case in the building sector. Here, the intermediate (2020) target poses the risk of creating lock-in effects. It is natural for a decision maker to focus on the closest target first and consider the long-term target first when the intermediate target is reached. A focus on a 20% (or 25% for Dalarna) reduction until 2020, however, could lead to lock-in effects, if the target is not regarded from a system perspective. Reducing energy use in the existing building stock with only 20% (25%) during refurbishment binds capital for probably five decades to come, capital that will no longer be available to go all the way to the 50% target. The solution to this dilemma is simple, however. Instead of reaching 20% reductions in all buildings until 2020, it should be aimed for reductions beyond 50% in those buildings that are refurbished until 2020. The sum of these more ambitious refurbishments should ideally add up to 20% (25%) in the entire building stock. After 2020, focus can be shifted to the remaining buildings and no lock-in effects are created.

To summarise, both building codes and the long-term savings objectives could be formulated in a better manner from the perspective of this thesis. Another layer of complexity with regard to energy efficiency will be added in the following chapter, where the so called rebound effect will be reviewed and discussed. As will become clear, building codes and energy savings targets will have to be complemented by other steering means in order to compensate for potential rebound effects.
3. Energy Efficiency, Jevons Paradox and the Rebound Effect – A Review

This chapter examines energy efficiency in general from a theoretical perspective, gives an overview of the historic discussion of energy efficiency efforts and presents in detail the research on the so called rebound effect, which may pose a serious challenge to decreasing energy use in the building sector. The chapter also provides some ideas as to how the rebound effect may be circumvented in order to be able to achieve real energy savings.

3.1 Introduction

If we want to save whales, Rudin [33] asks, would we want to eat whales that are slaughtered in a highly efficient manner or would we simply stop eating them? We have to ask the same question about energy consumption. If we want to save energy, and thereby reduce our greenhouse gas emissions, should we consume fossil fuels in a more efficient manner or should we not consume them at all?

In this chapter, we try to define what is meant by energy efficiency and look at some of the challenges that we can expect to encounter in this context. In contrast to the focus on energy efficiency as a response to the oil price shocks in the 1970’s and early 1980’s, the underlying premise today is that energy efficiency measures are introduced primarily as a means to decrease GHG emissions as a response to the threat of climate change. This premise can be confirmed not only by a range of policy support documents [34-36], but also by how energy efficiency targets are motivated in official documents (see also Chapter 2 above).

Energy efficiency can be approached from two directions [37]. First, relative prices can be changed by raising energy prices relative to e.g. labour costs. Second, the productivity of each unit of energy used can be increased by introducing new technology. However, as pointed out by Rudin [33], from an economic point of view, technical energy efficiency measures do not necessarily have to lead to decreased overall energy use. They can do so, but typically there is no linear relationship between technical energy efficiency improvements and overall energy consumption. Herring [38] even states that the opposite could occur, as the “effect of improving the
efficiency of a factor of production, like energy, is to lower its implicit price and hence make its use more affordable, thus leading to greater use”. This non-linear relationship has been coined the rebound effect and is well examined scientifically (see for instance Energy Policy 28 (2000), which was entirely devoted to the rebound effect).

Therefore it is important to define what we mean by the term energy efficiency and that we distinguish between energy conservation and energy efficiency, which in policy discussions often are used interchangeably [38]. Energy conservation should be defined as “reduced energy consumption through lower quality of energy services” [38]; examples of these could be lower room temperatures or speed limits for cars. Energy conservation is strongly influenced by regulation, consumer behaviour and lifestyle changes. Energy efficiency on the other hand should be defined as the “ratio of energy services out to energy input” [38] and can be seen as a technical process where old equipment is replaced by newer equipment. Energy efficiency is therefore considered a by-product of other social goals, such as productivity, comfort, monetary savings, competitive advantages, but also fuel scarcity [38]. However, it should be added that energy efficiency can be increased not only through technical progress, but also through behavioural change.

Already in 1865 it was discovered that the pursuit of greater efficiency may not necessarily lead to the actual conservation of resources. In chapter VII of his book The Coal Question, the English economist William Stanley Jevons stated that it is “a confusion of ideas to suppose that the economic use of fuel is equivalent to a diminished consumption. The very contrary is the truth” [39]. He was worried that the British coal reserves might become exhausted and had observed that efficiency improvements of the steam engines used had not lead to a decrease in coal consumption, but instead increased consumption as coal had become more affordable. The phenomenon became known as Jevons paradox. The paradox was revisited in 1992 by economist Harry Saunders who found evidence for energy efficiency measures leading to increased overall energy use, not only due to energy becoming relatively cheaper, but also due to energy efficiency leading to accelerated economic growth [40]. In this work the term “Khazoom-Brookes Postulate” was coined, as it was the economists Daniel Khazoom and Leonard Brookes whose work on energy efficiency had led Saunders to investigating the Jevons paradox from a modern angle. Today, rebound effect is the term used primarily in this context.
3.2 Background to the Rebound Effect

Within the context of energy efficiency, the rebound effect typically refers to the discrepancy between the expected outcome of an energy efficiency improvement and the actual result. Opinions on the relevance and magnitude of the rebound effect vary greatly in literature. On the one end of the scale, some authors dismiss the rebound effect as irrelevant (see [41] and [42] for an overview of the debate), while authors on the other end of the scale claim that energy efficiency measures always lead to an increase in overall energy use [33, 38]. Some economists, having subscribed to the economic growth paradigm, acknowledge that the rebound effect exists but do not see it as something negative as it in their view “translates technological efficiency improvements into economic growth” [37], thus disregarding that economic growth historically always has led to increased environmental degradation.

Correspondingly, there exist many different definitions of the rebound effect in literature [43], but according to Hanley et al. [44], the magnitude of the rebound effect can be defined as:

\[
R = \left[ 1 + \frac{\dot{E}}{\rho} \right] \times 100 \quad \text{Eq. 1}
\]

where \( R \) denotes the rebound effect expressed in percentage terms, \( \dot{E} \) the percentage change in physical energy use and \( \rho \) the percentage change in energy efficiency. When \( R \) has a value of 100%, a change in energy efficiency does not yield any change in overall energy demand. R values between 0 and 100% imply that an energy efficiency measure decreases overall energy use to some extent. R values of greater than 100% mean that overall energy use is actually increased due to the energy efficiency measure. This phenomenon is called backfire [44] and can be considered as an extreme case of the rebound effect.

A reduction in overall energy consumption in a growing economy can only be achieved if energy efficiency improvements exceed growth rates and if no backfire occurs. In that case, the required minimum rate of energy efficiency improvement \( i \) can be described with the following formula [37]:

\[
i = \frac{g}{(1 - rb)} \quad \text{Eq. 2}
\]

where \( g \) is the annual GDP growth and \( rb \) is the size of the rebound effect.

In order to be able to analyse and estimate the rebound effect properly, different types of rebound effects need to be distinguished. Herring [38] distinguishes three different types of rebound effects, while Greening et al. [43] describe four different types. A more sophisticated and comprehensive classification is suggested by Sorrell [42], see Figure 4 for a schematic overview.
Figure 4: Schematic overview of rebound effect classification (modified from [42]).

The actual energy savings are the difference between the calculated energy savings and the system-wide rebound effect, which depends on the time-frame (short, medium or long term) and the chosen system boundaries, which for the case of reductions in GHG emissions of course need to be global. The system-wide rebound effect is the sum of the indirect and the direct rebound effect. The indirect rebound effect can be decomposed into the embodied energy that is required to achieve the energy efficiency measure itself and secondary effects. Examples for these secondary effects can be [42]:

- Consumers may choose to spend the money saved from energy efficiency measures on other goods and services that need energy to be provided.
- Within production, sector-wide energy efficiency improvements can lead to lower product prices, which may induce increased consumption of these goods.
- The overall productivity of the economy will be increased by cost-efficient energy efficiency improvements, thereby usually triggering economic growth with its adverse environmental effects.
- Efficiency improvements on a large scale may decrease energy prices and thereby encourage an increase in energy consumption. This will also reduce the price of energy intensive goods and services to a greater extent than non-energy intensive goods and services and may increase the demand for these.

One indirect “rebound” effect that is overlooked by Sorrell [42] is one that points in the opposite direction. People who engage in energy efficiency activities may very well become more aware of their energy use and apply their knowledge to other areas of life. Although there is some evidence for this being true [45] the actual effects of this awareness increase would be difficult to quantify. The rebound effect may be further counterbalanced by
accelerated social diffusion of new behaviours, something that is not mentioned in the rebound effect literature either. There is strong evidence that new ideas and behaviours spread along the lines of social networks once a minority of people have adopted these new ideas and behaviours (see [45, 46] or [47] for a Swedish example). The process of social diffusion could have a substantial counterbalancing effect on the rebound effect, especially for those behaviours that are visible to others [45], but measurements are needed for a quantification (see Chapter 7.4.3 for further details on social diffusion).

Direct rebound effects can be divided into income and output effects as well as a substitution effect (Figure 4). From a consumer perspective, savings from energy efficiency are often used to consume more of the very good the energy efficiency of which was improved. A common example for this from the building sector is that indoor temperatures are increased after a refurbishment when insulation and windows are improved. Producers of consumer goods in turn may choose to increase output using the resources released through the energy efficiency measure, which will require increased inputs. The substitution effect implies that the use of the energy service, which has become cheaper after the energy efficiency improvement, is increased by substituting capital, machinery and labour (from a producer’s perspective) or other goods and services (from a consumer’s perspective) with the energy service. The substitution effect is especially dependent on the time perspective, since the longer the time frame considered, the more opportunities for substitution exist [37]. The time effect can be illustrated with the example of an empirical study of the effects of energy efficiency policy in Scotland where Hanley et al. [44] found that a slight rebound effect occurs after the introduction of the energy efficiency measures, which increases over time and finally turns into backfire. The development over time of the magnitude of the rebound effect differed between sectors. For electricity production, for example, backfire occurred immediately, i.e. the increase in competitiveness led to an immediate overall increase in production. The substitution effect is also dependent on the elasticity\(^3\) of substitution, which shows to what degree two goods, services or production factors can be substituted for one another. The higher the elasticity, the lower the reduction in overall energy use.

\(^3\) i.e. the “percentage change in one variable following a percentage change in another, holding the other measured variables constant” [48]
3.3 Estimating the Rebound Effect

According to Sorrell [49], it is very difficult to estimate direct rebound effects from an empirical perspective, as data is either unavailable or must be estimated at the cost of significant uncertainties. At the same time, very few studies attempt to quantify indirect rebound effects empirically (see below). Direct rebound effects are typically estimated using either a quasi-experimental approach or an econometric approach [48].

The quasi-experimental approach relies on measuring energy use before and after the implementation of an energy efficiency measure. The problem with this kind of approach, taking the case of space heating as an example, is that it is difficult to isolate the direct rebound effect, as it often cannot be differentiated between shortfall, temperature take-back and behavioural change. Shortfall is defined as the difference between actual and calculated energy savings, a part of which can be explained by temperature take-back, which is the change in mean internal temperature after the implementation of an energy efficiency measure. Correspondingly, part of the temperature take-back can often be explained with behavioural changes, which often are assumed to correspond to the direct rebound effect [48].

Econometric approaches are used more commonly and try to estimate the above mentioned elasticities based on data on energy demand, energy services and energy service efficiency. From these elasticities, the magnitude of the direct rebound effect of a measure can be estimated. If data availability is good, energy-efficiency elasticities are used, otherwise they are approximated using price elasticities. However, the use of price elasticities as a proxy for the direct rebound effect assumes that consumers react to decreases in energy prices in the same way as to energy efficiency improvements, which is likely to be flawed, as consumers react to a multitude of factors, and not only prices [48, 50]. Econometric approaches are usually based on secondary data that was collected for another purpose than estimating rebound effects, and may therefore not always be entirely suitable for the task [42].

Results from using both these approaches for estimating the direct rebound effect in the building sector are presented in the next section.
3.4 Quantifying the Rebound Effect in the Building Sector

Relatively few studies have attempted to quantify the rebound effect with regard to building sector energy efficiency measures. The most comprehensive study was performed by Sorrell [42] who reviewed over 500 studies to collect evidence on both direct and indirect rebound effects as well as backfire. This section gives an overview of these and other estimates that exist for both direct and indirect rebound effects in the building sector.

3.4.1 Direct Rebound Effects

Generally speaking, the magnitude of the direct rebound effect depends on both saturation effects and the cost of the energy efficiency improvement. Regarding saturation, Milne and Boardman [51] showed for example, that rebound effects can be expected to be higher for low-income groups in Britain, since the indoor temperature in their homes often is farther from the optimal level of thermal comfort, although these findings may be difficult to translate to other countries for various reasons. Regarding the cost of energy efficiency improvements, the rebound effect can be expected to decrease if energy efficient equipment costs more than less efficient equipment [42].

Greening et al. [43] reviewed North American literature on rebound effect estimates, the results of which for the building sector are presented in Table 4.
<table>
<thead>
<tr>
<th>Economic actor</th>
<th>End use</th>
<th>Potential size of the rebounda</th>
<th>Comments</th>
<th>Number of studies*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumers</td>
<td>Space heating</td>
<td>10-30%</td>
<td>The unmeasured part of this effect includes an increase in space conditioned and an increase in comfort.</td>
<td>26**</td>
</tr>
<tr>
<td></td>
<td>Space cooling</td>
<td>0-50%</td>
<td>The unmeasured part of this effect includes an increase in space conditioned and an increase in comfort.</td>
<td>9†</td>
</tr>
<tr>
<td></td>
<td>Water heating</td>
<td>&lt;10-40%</td>
<td>Reports of increased shower length or the purchase of increased water heating unit size indicate some indirect effects, which cannot be measured.</td>
<td>5−</td>
</tr>
<tr>
<td>Residential</td>
<td>Lighting</td>
<td>5-12%</td>
<td>An indirect effect in terms of an increase in operating hours was reported.</td>
<td>4−</td>
</tr>
<tr>
<td>Appliances</td>
<td></td>
<td>0%</td>
<td>Indirect effects in terms of the purchase of larger units with more features were reported.</td>
<td>2−</td>
</tr>
<tr>
<td>Firms (Short-run)</td>
<td>Lighting</td>
<td>0-2%</td>
<td>Changes in output were not reported. However, labour productivity probably improved.</td>
<td>4−</td>
</tr>
</tbody>
</table>

*aThese estimates are expressed as a percentage increase in consumption estimated to result from a 100% increase in energy efficiency (i.e. the estimated elasticity of demand times -100%)
*Grading system used for the quality of estimate:
**These studies are done with a number of methods that provide good correspondence of estimates
†These studies are done with only a moderate number of methods that show some variability in estimates.
These studies are done with only one or two methods and are inconclusive in results.
Note: All estimates assume a 10% increase in efficiency of fuel consumption.
Haas and Biermayr [52] cite a study by Scheer [53] who investigated the ratio between calculated and actual savings in 11 building refurbishments and concluded that the average direct rebound effect for them was 30%. Rebound effect values between 25 and 29% were found by Klein [54] for U.S. residential space heating, as reported in Sorrell [42]. This rebound effect in connection to space heating can according to Haas and Biermayr [52] be explained with what they call a service factor $f_s$, which is the ratio between the actual space heating energy demand $E_{SH}$ and the theoretical space heating energy demand $E_{SHth}$. In their model, $f_s$ is a function of individual consumer behaviour, type of heating system, building type, income, price of service, number of dwellings per building, fuel price, fuel type, thermal quality of the building, indoor temperature etc. Hong et al. [55] report rebound effects of 65 to 78% for retrofit building insulation, but acknowledge that the calculated savings were flawed since they idealised the performance of the retrofit insulation. Milne and Boardman [51] presented rebound effect figures of 0 (at 20°C indoor temperature before the refurbishment), 20 (at 19°C) and 30% (at 16.5°C) for different insulation and glazing improvements, but their results are difficult to translate to Swedish circumstances, as they analysed low-income households with energy standards far below Swedish standards. Sorrell et al. [48] summarise much of the existing research that has attempted to quantify direct rebound effects and suggest the rebound effect values presented in Table 5. Note that there exists some overlap between Table 4 and Table 5, although it has not been possible to identify which studies were reviewed by both Sorrell et al. [48] and Greening et al. [43], as the sources underlying Table 4 are not disclosed in Greening et al. [43].

Table 5: Econometric estimates of the long-run direct rebound effect for household services in the OECD [48].

<table>
<thead>
<tr>
<th>End-use</th>
<th>Range of values in evidence base (%)</th>
<th>“Best guess” (%)</th>
<th>No. of studies</th>
<th>Degree of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating</td>
<td>0.6-60</td>
<td>10-30</td>
<td>9</td>
<td>Medium</td>
</tr>
<tr>
<td>Space cooling</td>
<td>1-26</td>
<td>1-26</td>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>Other consumer energy services</td>
<td>0-41</td>
<td>&lt;20</td>
<td>3</td>
<td>Low</td>
</tr>
</tbody>
</table>

Sorrell et al. [48] also reviewed 12 quasi-experimental studies that confirmed that the direct rebound effect is in the range of 20%. It is pointed out, however, that the degree of confidence is rather low, especially regarding space cooling and other consumer energy services, as the studies reviewed were rather outdated and were found to have some methodological flaws.
Nässén and Holmberg [56] estimated the magnitude of the rebound effect specifically for the Swedish building sector using an econometric model. Estimates were obtained for both electricity and space heating, with an expected direct rebound effect of 9% and 14% respectively. The rebound effect for space heating being in the lower end of the range shown in Table 5 is likely to be due to the higher initial temperatures (and building standard) in Swedish homes, i.e. a saturation effect.

3.4.2 Indirect Rebound Effects
No matter what the magnitude of the direct rebound effect is, the indirect rebound effect plays an at least equally important role. For households this means that the part of their budget that is not used for the energy service whose efficiency was improved will most likely be used for other types of consumption [57].

It has to be noted, however, that many energy efficiency investments in the building sector require large initial investments which may not release resources for the consumers. This was investigated by Nässén and Holmberg [56] who compared a break-even investment with a profitable investment in the building shell and found that the (direct) rebound effect for the former can be expected to amount to 8%, while a profitable investment would yield a rebound effect of 15%.

Very few studies have attempted to estimate indirect and economy-wide rebound effects. Sorrell [42] reports that the different modelling approaches that were reviewed all have considerable methodological weaknesses. This does not allow for any conclusions on the magnitude of the indirect rebound effect to be drawn. However, results from Computable General Equilibrium (CGE) models suggest that economy-wide rebound effects can exceed 50% and that backfire could occur, although no direct mention of the building sector is made here.

3.4.3 Backfire
Sorrell [42] extensively reviewed evidence on the occurrence of backfire from energy efficiency improvements and reports that arguments from both sides – for and against backfire – are unconvincing. He states that “most economists assume that the increased availability of energy inputs has only made a small contribution to economic growth, owing to the small share of energy in total costs” and that ecological economists argue against this view stating that the opposite has been the case, that increased energy inputs have been “the primary driver of economic growth”. A closer look at how modern industrial society is functioning from a technical point of view may suggest that the ecological economists are closer to the truth than conventional economists.
To summarise the results of the different studies, it can be said that the magnitude of the rebound effect is highly uncertain, especially regarding space cooling, water heating and lighting. Somewhat higher confidence exists for space heating. Given the kind of threat the rebound effect poses to efforts towards improved energy efficiency, a question that needs answering is what strategies exist for preventing the occurrence of rebound effects or even backfire.

### 3.5 Solving the Rebound Effect Dilemma

As Sanne [57] puts it, “the task prompted by the rebound effects is to prevent beneficial gains in efficiency being translated into an ecologically maleficient consumption”. Another way to put the challenge is to say that the rate of increased energy efficiency per output unit must outpace the growth rate of the output itself [37]. Taking Sweden as an example, this was not quite the case for the period 1971 to 2007. While the primary energy supply per unit of GDP decreased by 37%, the overall primary energy supply still increased by 38% during this period. The same can be said about the OECD as a whole, where primary energy supply per unit of GDP decreased by 41% during the same period, whereas the overall primary energy supply increased by 66% [58]. Thus, GDP increased at a much higher rate than energy efficiency, and the prerequisite for an overall reduction in energy use as defined in Eq. 2 has not been fulfilled. Birol and Keppler [37] therefore suggest balancing technical energy efficiency measures with changes in relative prices between energy, capital and labour, in order to be able to achieve the reductions in overall energy use that are necessary to fulfil climate and other objectives.

In theory, high energy prices mean that technologies are used that are more capital and/or labour intensive. Correspondingly, low energy prices entail the use of technologies with relatively higher energy input and lower capital and/or labour inputs. Of course this depends on the degree of substitutability between the different factors of production. Furthermore, during times of high energy prices, irreversible energy efficiency improvements will occur [42], as for instance thermal insulation is unlikely to be removed when energy prices fall again. From this, it is natural to conclude that the prices of energy-using and energy-saving technology as well as energy prices themselves are key variables for dealing with energy efficiency [37], although irrational (from an economic point of view) user behaviour is not included in this line of thought.

Instruments that can be used to influence relative energy prices are taxes on energy or energy-intensive products, subsidies for alternative processes or products and different types of trading schemes such as carbon trade or white certificates. A secondary effect of changing the relative price of
energy is according to Birol and Keppler [37] that more efforts will be put into energy efficiency research and development, which in turn will affect energy efficiency positively. Increasing the relative price of energy has thus a positive feedback effect on energy efficiency. Thus, Birol and Keppler [37] argue that price signals and support for technology improvement need to be combined in order to obtain “economic and environmental least-cost solutions”. Sanne [57] sees the problem from a slightly different angle and suggests three different ways of ensuring that energy efficiency measures deliver ecologically desirable results. The resources released through energy efficiency can either be taken out of circulation or be diverted to other parts of the economy where they do less harm. One option in this respect could be to use the resources made available from efficiency gains to support the roll-out of renewable energy technology, which would speed up the energy transition on the supply side, while energy demand would simultaneously decrease (and ideally stay low). A third option is to refrain from releasing resources by decreasing production. An example of this would be to transform increased energy efficiency into leisure time instead of increasing wages, something that Knight et al. [59] found to be an “attractive target” for sustainability policy, since working hours contribute significantly to impacts on the environment in the OECD countries. Sanne [57] is sceptical towards taxation directed to avoiding the rebound effect, as the taxes collected eventually will be used to some degree for consumption. Alcott [41] finally argues for rationing as an attractive means to counter the rebound effect.

One could argue that the building sector is one of the better sectors in which to increase energy efficiency. Investments are often long-term (such as replacing windows, adding extra insulation or upgrading heating systems) and payback times are often very long, all of which could explain the relatively low magnitude of the rebound effect observed in the sector. However, the rebound effect could be decreased further if public debate could shift from discussing energy efficiency in terms of profitability to discussing it in terms of lifestyle, convenience etc. If energy efficiency could be made as attractive as replacing one’s kitchen, owning a car or spending holidays in far-away countries – all of which are anything but profitable – then people’s capital would be locked up for years or even decades, causing little harm and potentially even locking up carbon in organic building materials. How such a shift in mind-set could be achieved is explored further in Chapter 7 below.

How the rebound effect dilemma is to be solved is primarily an issue for policy makers and acknowledging the problem for instance in official energy efficiency strategies would be a good start. That there may be still some way to go before the challenges connected to energy efficiency are recognised on the political scene, too, becomes obvious when reviewing official analyses. Sorrell [42] names the famed Stern report [60] as an example, where rebound effects are overlooked entirely. The same can be said for other
policy support documents that are highly supportive of energy efficiency as a means to decrease GHG emissions but ignore the issue altogether (such as [35, 61]) or bluntly state that rebound effects were not modelled [36]. Another example is the 2007 IPCC report, where it is solely noted that “the literature is divided about the magnitude of [the rebound] effect” [62]. On the Swedish national level the lack of discourse can be illustrated by a report by the Swedish “Dwelling Committee” (Bostadsutskottet) from 2005. There, it is stated that energy must be used more efficiently in all areas and all sectors in order to be able to fulfill the vision of a sustainable society. In the same paragraph it is said that energy efficiency is expected to support economic growth by increasing consumers’ purchasing power [63]. The possibility that increased purchasing power can be expected to entail increased resource consumption and thereby thwart the sustainability vision appears to be ignored. On the EU level a research project on the rebound effect showed that there is at least some interest in addressing the issue from EU policy makers [64], which eventually should trickle down to the member states.

3.6 Conclusions
The rebound effect potentially poses a real threat to attempts to improve energy efficiency in society. Numerous studies that have tried to quantify the actual magnitude of this threat, but there still exists much uncertainty as to how serious a challenge the rebound effect poses. This is especially due to the difficulties in quantifying the indirect rebound effect. Relatively few studies have been able to provide rebound effect estimates for the building sector, and even fewer are applicable to the relatively high standard conditions in Sweden. A 10-15% direct rebound effect might be a decent guess, and the relatively high cost of many energy efficiency improvements may prevent the risk of backfire through the indirect rebound effect. Despite these considerable uncertainties, policy makers are advised to take the rebound effect challenge seriously and plan for preventive action. The most effective preventive instrument is potentially the conversion of efficiency gains into more leisure time, as it does not create the possibility to use efficiency gains for increased consumption. However, this instrument may entail an initial rebound effect, since savings are at risk of being converted into increased consumption, when people find that they suddenly have much more time to spend on leisure activities. Yet, making use of such an instrument on a larger scale would require a substantial shift in values in society and would radically alter the prevalent growth-oriented economic model. This is unlikely to happen in the short-term. From an individual household perspective, however, this could be a viable strategy to pursue, see Chapter 6 for an example of this.
4. Characterising the Building Stock

This thesis covers primarily detached one- and two-dwelling houses (henceforward called detached houses) and in this chapter it will be shown why these were focused upon. A characterisation of the building stock in the county of Dalarna will be presented and estimates of energy use in the sector will be made. The research presented in this chapter is reported in-depth in [65].

4.1 Introduction

In Sweden, the focus of most policy and media has been on the (mostly multi-dwelling) buildings dating from the ‘one million homes’ era between 1965 and 1975. In this period some one million dwellings were constructed, often with poor quality materials [66]. While focussing on these buildings may be justified in the metropolitan areas of Stockholm, Malmö and Gothenburg, the challenges in many other parts of the country are of a different kind.

In Sweden as a whole, dwellings in detached houses account for 44% of the total heated housing space area [67], but in the less densely populated parts of Sweden, where about 60% of the population live [68], this proportion can be much higher. Yet there are no national programmes specifically addressing energy refurbishment in existing detached houses.

The most prominent actor in this area has been the non-governmental Swedish Association for Building Preservation, which has published a book on energy efficiency in older buildings [70] and has held a number of seminars on the same topic targeted at home owners. The relative neglect of existing detached houses in national energy reduction policies has led to a gap between national policy objectives, often related to new buildings and multi-dwelling houses, and the reality many regional building sector stakeholders are facing. The 50% reduction target cannot be reached without addressing energy efficiency in existing detached houses, which are predominant in the rural regions of Sweden.

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4 The only programmes addressing detached houses are at the time of writing a programme for tax-reduction for general refurbishment and grants for solar cells [69].
A further challenge in the less densely populated counties is that refurbishment costs are fairly similar across the entire country, while property prices are not. In the twelve most sparsely populated counties, which have just below a third of the population, house prices were on average 30% below the national average in 2000–2011 [71]. In these regions investments in refurbishment will be less worthwhile since they are not as likely to be recouped by an increase in property value.

Working with the energy use of buildings at a regional or local level is made more difficult by the lack of detailed statistics and the restrictions on cross-connections between different statistical datasets, such as socio-economic information and the characteristics of the building stock. Information on the ownership, age and floor area of the building stock is not available publicly. Official energy statistics are produced only on an aggregated level, based on questionnaires that are sent out to building owners all over the country. More data on detached houses was obtained through an extended survey conducted in 2010 in which questionnaires were sent to the owners of 73,000 detached houses, compared to 7,000 questionnaires sent out in previous surveys [72]. The aim of this extended survey was to improve energy statistics at a regional level. Data on average energy use, total energy use, as well as on the type of fuel used was given at a county and in some cases also on a municipal level. However, the results still proved to be too aggregated to allow for detailed analysis; for example, no information was given on the regional energy use of houses in different age groups.

The combined difficulties posed by the policy shortcomings in regard to the housing stock in rural regions, the regional variations in building activity and property prices, the cultural regulations and the lack of statistics add up to a need for new strategies to support local and regional energy efficiency policy. As a first step, it is necessary to gain a deeper understanding of the current regional building sector characteristics and the consequences for stakeholders these might entail. Thereafter it can be valuable to analyse trends in building stock development in order to obtain some kind of reference, both with respect to its physical characteristics and the impact of demographic development on the residential sector. Building sector development depends in theory on many factors, some of which were assessed for the county of Dalarna in order to forecast the size and structure of the residential sector in 2050, using some of the data obtained in the first step.

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5 Jönköping, Kronoberg, Kalmar, Blekinge, Värmland, Örebro, Dalarna, Gävleborg, Västernorrland, Jämtland, Västerbotten and Norrbotten.
4.2 Method

Statistics based on taxation data, including parameters such as age, space area, type of building, grid coordinates and type of owner for most buildings in the county were purchased from Statistics Sweden (SCB). The statistics were used to characterise the buildings stock in detail. The results were presented to and discussed at several meetings with a stakeholder group composed of representatives from the environmental and planning departments at the County Administrative Board, as well as representatives from the Swedish Construction Federation, local utilities and housing companies. This was done both to receive further research input, as well as to communicate research findings to the regional actors.

Since no regional or local data on energy use were available, estimates of use of purchased energy were based mainly on national building energy statistics for 2008 [73-75]. For most non-residential premises and all one-, two- and multi-dwelling houses in permanent use in the county, average purchased energy use per square metre, which is a function of the age and type of use of the building, was multiplied by the size of the heated area. For detached houses, energy use as a function of residential and non-residential floor area and building age was used as an input. This calculation yielded not only an estimated energy use for most of the building stock, but also enabled calculation of the total energy use per municipality, building age group, owner group, etc. Leisure home energy use was estimated from rather rough findings by the Swedish Energy Agency [76]. The results were validated by using energy supply data for the region from SCB [77] and the Swedish Energy Agency [78], with data from the 2010 energy use survey [72] and energy performance certificate (EPC) data obtained from the Swedish National Board of Housing, Building and Planning (Boverket). However, the datasets used are not entirely comparable. The annual energy surveys present data for that specific year, not adjusted for differences in temperature compared to the reference time frame of 1961–1990, while the EPC data is adjusted for temperature differences. EPC data was available for 6,023 detached houses in permanent use (7.0% of total in the county), 205 (0.8%) leisure homes and 3,836 (89.3%) multi-dwelling houses. This data covers a much larger portion of the housing stock in the county than the official energy statistics.

Regarding trends in the building sector, average new construction rates for the period of 1993 to 2008 were used to forecast the number of new dwellings from 2009 and onwards. The findings were refined with data for refurbishment rates, based on SCB data [80]. This data is based on building permits granted by the municipalities for refurbishment of multi-dwelling houses. Before 2008, the statistics were refined with data from the County

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6 2008 was about 2°C warmer than average while 2010 was 1°C colder than average [79].
Administrative Boards on grants given for refurbishment of these buildings. This support scheme was however removed in 2008. This implies that only refurbishments that require a building permit are included in the statistics. Furthermore, the refurbishments do obviously not necessarily imply energy use improvements, but they were nonetheless used as a basis for the forecast since they potentially could be an opportunity for energy refurbishments. Since no data on refurbishment of detached houses is available, it was assumed that the same refurbishment rate as in multi-dwelling houses is applicable. Demolition rates for both detached houses (based on own analyses of the taxation data used for characterisation of the building stock) and multi-dwelling houses (based on [81]) were also taken into account in the forecast. The findings were used to illustrate the energy savings levels required in the different parts of the building stock to reach the 50% reduction objective.

A second trend that was analysed was an expected demographic development in the county, based on average birth rates for the period of 1993 to 2008 (and expected death rates until 2050) in order to take into account the actual expected need of dwellings in the county, based on data from SCB [82-84]. In a subsequent step, the analysis was refined by taking into account trends in numbers of residents per dwelling.

4.3 Results

4.3.1 Building Stock Structure

The analysis of the building sector revealed that 59% of the heated area in Dalarna’s housing stock is found in detached houses in permanent use, while leisure homes account for 16% of the heated area (see Table 6). Multi-dwelling houses account for only 25% of the total heated area. Almost 80% of the buildings were constructed before 1981. Findings for non-residential premises, which are excluded in this thesis, are described in detail in [65].
Table 6: Proportion of total heated area for Dalarna by type of building and age group.

<table>
<thead>
<tr>
<th>Age group</th>
<th>Multi-dwelling homes</th>
<th>Detached houses for permanent use</th>
<th>Leisure homes</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-1940</td>
<td>1.0</td>
<td>17.6</td>
<td>3.7</td>
<td>22.3</td>
</tr>
<tr>
<td>1941–1960</td>
<td>6.5</td>
<td>11.1</td>
<td>3.0</td>
<td>20.7</td>
</tr>
<tr>
<td>1961–1970</td>
<td>6.2</td>
<td>6.9</td>
<td>2.1</td>
<td>15.2</td>
</tr>
<tr>
<td>1971–1980</td>
<td>4.7</td>
<td>12.9</td>
<td>4.0</td>
<td>21.5</td>
</tr>
<tr>
<td>1981–1990</td>
<td>4.1</td>
<td>6.5</td>
<td>1.9</td>
<td>12.4</td>
</tr>
<tr>
<td>1991–2000</td>
<td>2.3</td>
<td>2.2</td>
<td>0.7</td>
<td>5.2</td>
</tr>
<tr>
<td>post-2000</td>
<td>0.4</td>
<td>1.4</td>
<td>0.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Total</td>
<td>25.3</td>
<td>58.7</td>
<td>16.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

76% of the housing stock is owned by private individuals, indicating a fragmented ownership structure with as many as 100,000 individual house owners existing in the county. Only 10% of the housing stock is owned by public housing companies, who on the national level own 17% of the housing stock [85]. Housing cooperatives, who on the national level own a whole 22% of the housing stock [85], account for only 8% in Dalarna. The remaining 6% of the housing stock are owned by Swedish corporations (4%) and other types of owners (2%).

![Figure 5: Ownership of the housing stock in Dalarna in % of total area.](image)

The renewal rate of the building stock is low, with new-built rates in 2008 ranging from 0.8% of the total stock for leisure homes (mainly in the mountainous parts of the county, which have a growing skiing and hiking industry) to 0.4% for detached houses in permanent use and 0.2% for multi-dwelling houses (Figure 6). The turnover has been low for the last two
decades, which is also reflected by the very low proportion of buildings constructed after 1990 (Table 6). The drastic drop in new construction in the early 1990s is explained by a tax reform in 1991 that decreased the allowance of tax deductions for interest payments on loans from 50% to 30%, followed by a severe financial crisis. These figures can be compared to the building stock renewal rate in other European countries, which is reported to be around 1% [86, 87].

![Figure 6: Renewal rate of the building sector in Dalarna in % of the total building stock for one- and two-dwelling houses, leisure homes and multi-dwelling houses.](image)

4.3.2 Energy Use

The key role of detached houses in decreasing energy consumption in the building sector is confirmed by the energy use figures. Total energy use (excluding household electricity) in permanently used detached houses is estimated to be 1,414 GWh for 2008 and 1,493 GWh for 2010. The corresponding figure obtained from the EPC database is 1,669 GWh/year (see Table 7). The figures for 2008 and 2010 were not corrected for climatic variation while this was done for the figures from the EPC database.

What the table does not show is that houses constructed before 1981 account for roughly 90% of the total energy use in this category. Energy use in leisure homes is estimated to be 154 GWh/year based on the above-mentioned survey for 2001 [76], while EPC data puts the estimate much higher, at 376 GWh/year. Multi-dwelling houses are estimated to have used 557 GWh/year in 2008, 612 GWh/year in 2010 and 602 GWh/year based on
EPC data. These figures can be compared to energy supply data for 2008 [77] and 2010 [78], which were produced independently from energy use statistics. The figures match rather well with the modelled estimates, with the exception of the 2008 figure on energy supply to multi-dwelling buildings.

*Table 7: Estimated housing sector energy use in Dalarna by building category*

<table>
<thead>
<tr>
<th>Building Category</th>
<th>Energy use per year (excl. household electricity) in GWh</th>
<th>Energy supplied per year (excl. household electricity†) in GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2008</td>
<td>2010</td>
</tr>
<tr>
<td>Detached houses in permanent use</td>
<td>1,414 (67%)</td>
<td>1,493 (66%)</td>
</tr>
<tr>
<td>Leisure homes</td>
<td>154 (7%)**</td>
<td>154 (7%)**</td>
</tr>
<tr>
<td>Multi-dwelling houses</td>
<td>557 (26%)</td>
<td>612 (27%)</td>
</tr>
<tr>
<td>Total</td>
<td>2,126</td>
<td>2,259</td>
</tr>
</tbody>
</table>

*Values according to data from Boverket’s EPC Database.**


†No specific data on household electricity use given in the sources. Household electricity use was estimated to 300 GWh for detached houses in permanent use and 150 GWh for multi-dwelling houses and was subtracted from the total figures. See [65] for details.

Table 8 below provides information on the types of heating systems used in Swedish and North Middle Swedish detached houses respectively. Electric heating includes air sourced heat pumps, direct current electric heating and electric central heating. Oil-fired heating systems are barely existent in Sweden, while biofuel-fired systems and heat pumps (both ground sourced and water sourced) have a large share. Dalarna and the surrounding counties in North Middle Sweden are characterised by a larger share of both biofuel-fired and heat pump based systems, while electric heating and district heating have a lower share than the national average.
Table 8: Heating systems used to heat detached houses in Sweden and North Middle Sweden [21].

<table>
<thead>
<tr>
<th></th>
<th>Sweden (%)</th>
<th>North Middle Sweden (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric heating only</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Oil only</td>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>Oil and electricity</td>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>Biofuel and electricity</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Biofuel only</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Heat pump and electricity</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Heat pump and biofuel</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Heat pump only</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>District heating</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>

*Total percentage errors due to statistical uncertainties.
**Corresponding to national area of Sweden NUTS SE06, including the county of Dalarna.

The official Swedish energy statistics provide very little information on the use of household electricity, i.e. the use of electricity for lighting and appliances such as computers, washing machines, dry tumblers, fridges, freezers, vacuum cleaners, televisions etc.. In general, household electricity use in detached houses is believed to have increased by 58% between 1970 and 2011, from 3,800 kWh to about 6,000 kWh per year in 2011 [21]. However, part of the increase is believed to be caused by greater electricity use for operating ventilation systems, circulation pumps and floor heating. A detailed study of electricity use in 400 Swedish households revealed a total household electricity use of approximately 4,000 kWh/year [88], which may indicate that a whole 2,000 kWh per year are used for operating the above named systems. A backward calculation of total electricity use figures including household electricity subtracted by electricity use without household electricity (from [73]) showed that household electricity use in detached houses in Dalarna is in the region of 3,400 kWh per year. This indicates further how uncertain statistics on household electricity use are.

4.3.3 Future Trends

**New construction, demolition and refurbishment in Dalarna**

New construction rates averaged 0.19% for multi-dwelling buildings and 0.27% of the total building stock for detached houses during the period of
1993 to 2008 (cf. Figure 6). The average demolition rate of multi-dwelling buildings was found to be 0.38%. Demolition rates of detached houses were much lower, averaging 0.0056% during the same time period. The average refurbishment rate was 1.19% (see above). Assuming a linear development of these variables from 2009 and onwards yields the results presented in Figure 7. The total number of dwellings would thus increase by 13% from 2008 to about 160,000. The share of dwellings in multi-dwelling houses would decrease from 40% in 2008 to 33% in 2050 due to the lower rate of new construction and higher rate of demolition. Approximately 43% of the total number of dwellings will have undergone some form of refurbishment by 2050. The share of dwellings constructed after 2008 is 7.9% for multi-dwelling buildings and 10.3% for detached houses, all under the assumption that trends for the period 1993 to 2008 will persist until 2050.

![Figure 7: Forecast of building stock development based on trends for 1993 to 2008.](image)

Assuming that energy use is reduced in refurbished and new built houses only, a 90% decrease in energy use compared to the current average would have to be achieved in order to fulfil the 50% reduction objective until 2050, which does not even take into account potential rebound effects. This corresponds to an energy use for heating and hot water in these houses of
approximately 13 kWh/m², which is far below the requirements set in the current building codes (cf. Tables 1 and 2).

**Population trends**

With an average life expectancy of 78.6 years for men and 82.7 years for women [84] we can expect about half of Dalarna’s population to have died by 2050, taking into account the county’s current age structure. To keep the population level at least constant and to compensate for population loss from migration away from the county, too, an average of about 3,200 people need to be born annually. Birth rates in the recent past, however, have been much lower, averaging at 2700 people per year between 1993 and 2008. Between 1969 and 2008 the required birth rate of 3,200 births per year was exceeded during the seven year period from 1987 to 1993. Furthermore, the period 1993 to 2008 was also characterised by a net population loss due to migration away from the county. On average a net figure of 340 people moved from Dalarna during the period. Therefore, current trends point to a decrease in total population until 2050 to about 240,000 people, compared to a total population of 275,000 in 2008.

Another issue that was considered is the number of residents per dwelling. The overall household size has been decreasing linearly ($R^2=0.92$) from 2.14 to 1.96 persons per dwelling between 1990 and 2008 and can be expected to be as low as 1.77 persons per dwelling in 2050 if current trends continue. For the population forecast this means that about 130,000 dwellings would be required in 2050. When comparing these figures with the values obtained from the extrapolation of demolition and new construction rates in Figure 7, it becomes obvious that the number of dwellings in 2050 would be more than sufficient (with a surplus of 30,000 dwellings), despite the assumption that fewer and fewer people would occupy each dwelling.
4.4 Discussion

The results from this analysis, i.e. that detached houses account for roughly 75% of the energy use in the housing stock, came as a surprise to local building sector stakeholders, who for years had been focusing their activities on multi-dwelling and non-residential premises, which is also the area where most energy refurbishments have already taken place. Detached houses had only been considered from the perspective of efforts to increase new construction [89], which is no different from how detached houses have been treated on the European level [90]. However, the findings were readily accepted by representatives of the County Administrative Board, and detached houses have become a focus area in the most recent Energy and Climate Strategy for Dalarna [18]. Furthermore, Dalarna’s building sector stakeholder association (Building Dialogue) has now incorporated refurbishment of detached houses into their activities through a project that aims at identifying (and subsequently realising) refurbishment potentials in a few sample houses in the region.

Regarding energy use estimates, EPC data constitutes the best source for data on building energy use because the dataset is much larger than the official statistics and specific to the county, and also because the data is normalised with respect to temperature variations. However, the magnitude of energy use in leisure homes is still very uncertain. Energy supply data offers the most reliable information for leisure homes as the EPC data is likely to be misleading. Leisure homes are not required to be energy certified when sold, and the ones that are certified are not likely to be representative.

Making connections between the building stock dataset and other data, for instance socio-economic datasets (including occupant age, income etc.) would have improved the analysis, but permission for this was not granted by SCB. Other countries are less restrictive and provide statistics more freely. In Denmark, for example, such comparative studies are possible and have yielded interesting findings on the correlation between household income and energy use [91, 92]. Performing such analyses are relevant especially given the highly fragmented ownership structure in the county, with as many as 100,000 individual home owners, which all need to reduce energy use in their houses.

Regarding the use of household electricity, the limited and partly contradicting figures in the statistics reflect the lack of an integrated perspective on energy use in buildings in Sweden. The building codes do not set any requirements on the use of household electricity (as is done for instance in Germany or Austria), although household electricity use can have a substantial share of total energy use and contributes to internal heat gains. This problem will grow as houses become more energy efficient in the future.
The results from the trend analysis show more than anything that a continuation of current trends is not an option if the long-term savings objective is to be achieved. The construction of new buildings is too limited to seriously influence energy use in the county. At the same time the roughly estimated refurbishment rates are too low to decrease energy use in existing buildings, even if they all were refurbished to very low energy use levels.\(^7\) The demographic trends point into a different direction, however. With current trends, even taking into account ever smaller household sizes, there would be an oversupply of dwellings of more than 20% by 2050. Substantial absolute energy savings would thus be achieved automatically through the forecasted population decline.

Clearly, current trends need to be broken and there are several options for this. Demolition rates could be increased to get rid of existing, highly energy consuming buildings once they have come to the end of their technical life span. In this respect, houses which are most expensive to refurbish should be targeted first. However, aspects of cultural and architectural values need to be taken into consideration with such an approach. Another option would be to target existing houses with the aim to achieve as far-reaching energy savings as feasible. This route will be examined at great detail in the remainder of this thesis. Influencing demographic trends is less straightforward and is outside the scope of this thesis. However, it needs to be acknowledged that the demographic change will play an important role for the future of the building sector in Dalarna.

4.5 Conclusions

The analysis showed that detached houses, especially those constructed before 1981, deserve special attention in the rural areas of Sweden, despite the current focus on multi-dwelling buildings from national policymakers. Furthermore, extrapolating current trends in building stock development showed that the 50% savings target cannot be achieved unless existing buildings are addressed specifically. This opens quite a few research opportunities and subsequent chapters of this thesis will explore the possibilities for energy savings in older, detached houses.

\(^7\) It needs to be added here, however, that refurbishment rates in detached houses are likely to be considerably higher than in multi-dwelling houses, cf. [93].
5. Energy Savings Potentials in Detached Houses

5.1 Introduction
Detached houses constructed before 1981 were identified as the single largest consumers of energy in the building stock in Dalarna. These are also likely to be in most need of refurbishment, and the analysis presented in this chapter seeks to identify energy savings potentials in this part of the building stock. The starting point for the analysis was that refurbishment measures should be relatively easy to implement and that historic, cultural and architectural values in the houses should not be jeopardised by the implementation of the measures. More details on the analysis can be found in a working paper on the analyses presented in this chapter [94].

5.2 Method
Eight different sample houses were identified based on the building sector structure identified in Chapter 4. Each of the houses was characterised based on building data given by Björk et al. [95], who describe the architecture of Swedish detached houses in great detail. Table 9 provides an overview of the most important characteristics of the eight sample houses. The buildings were then modelled using building energy simulation software (VIP Energy v. 1.5.6, see [96] for further information on the software). VIP Energy was chosen as it was relatively simple to use and served the purpose of providing a general overview of the savings potential in existing buildings without the need to specify too many details. For each building a number of energy savings measures were simulated, both individually and in combination with other measures, and their costs calculated.
<table>
<thead>
<tr>
<th>Sample house</th>
<th>Date of construction</th>
<th>Area (m²)</th>
<th>Storeys</th>
<th>Type of foundation</th>
<th>Type of window</th>
<th>Wall characteristics</th>
<th>Attic insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800-1890</td>
<td>240</td>
<td>2</td>
<td>Crawl space</td>
<td>2- pane</td>
<td>Massive timber logs, 250 mm</td>
<td>200 mm wood shavings</td>
</tr>
<tr>
<td>2</td>
<td>1890-1920</td>
<td>90</td>
<td>1 1/2</td>
<td>Cellar (unheated)</td>
<td>2- pane</td>
<td>Half-timber construction (150 mm) with insulation of wood shavings</td>
<td>150 mm wood shavings</td>
</tr>
<tr>
<td>3</td>
<td>1921-1930</td>
<td>150</td>
<td>2</td>
<td>Cellar (unheated)</td>
<td>2- pane</td>
<td>Solid deal wall (75 mm)</td>
<td>140 mm saw dust</td>
</tr>
<tr>
<td>4</td>
<td>1931-1940</td>
<td>90</td>
<td>2</td>
<td>Cellar (unheated)</td>
<td>2- pane</td>
<td>Deal frame (60 mm) + mineral wool (50 mm)</td>
<td>160 mm saw dust</td>
</tr>
<tr>
<td>5</td>
<td>1941-1950</td>
<td>90</td>
<td>2</td>
<td>Cellar (unheated)</td>
<td>2- pane</td>
<td>Deal frame (60 mm) + mineral wool (50 mm)</td>
<td>160 mm saw dust</td>
</tr>
<tr>
<td>6</td>
<td>1951-1960</td>
<td>105</td>
<td>1</td>
<td>Cellar (partly heated)</td>
<td>2- pane</td>
<td>Post-and-beam construction, 120 mm mineral wool</td>
<td>80 mm mineral wool</td>
</tr>
<tr>
<td>7</td>
<td>1961-1970</td>
<td>135</td>
<td>1</td>
<td>Concrete slab</td>
<td>2- pane</td>
<td>Post-and-beam construction, 100 mm mineral wool</td>
<td>125 mm mineral wool</td>
</tr>
<tr>
<td>8</td>
<td>1971-1980</td>
<td>150</td>
<td>1 1/2</td>
<td>Concrete slab</td>
<td>3-pane</td>
<td>Post-and-beam construction, 187 mm mineral wool</td>
<td>245 mm mineral wool</td>
</tr>
</tbody>
</table>
In addition to the physical characteristics of the houses, a number of general parameters were set for all buildings, see Table 10. The town of Borlänge in central Dalarna was chosen as the climate station, with climate data representing average values for the period 1993 to 2003. All buildings were assumed to be somewhat sheltered from winds, with wind speeds reduced to 45% of the climate data value. Reflection of sunlight from the ground was set to 30%.

*Table 10: General simulation input parameters.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural ventilation in buildings constructed before 1961</td>
<td>0.5</td>
<td>Turnovers/h</td>
<td>[97]</td>
</tr>
<tr>
<td>Natural ventilation in buildings constructed after 1961</td>
<td>0.3</td>
<td>Turnovers/h</td>
<td>[97]</td>
</tr>
<tr>
<td>Energy from residents</td>
<td>80</td>
<td>W/person</td>
<td>[98]</td>
</tr>
<tr>
<td>Presence of residents</td>
<td>14</td>
<td>h/day, person</td>
<td>[98]</td>
</tr>
<tr>
<td>No. of residents</td>
<td>2.53</td>
<td>Persons/house</td>
<td>[65]</td>
</tr>
<tr>
<td>Heat gain from occupants</td>
<td>118</td>
<td>W/house</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

The savings measures were selected based on whether they were feasible from a cost perspective, from a technical perspective, and in terms of their impact on the cultural and architectural values of each building. Only measures that would allow residents to remain in their homes during refurbishment were included. Measures that would greatly alter the exterior appearance of the building, such as external wall insulation, were ruled out. Measures using heat recovery from ventilation were not included since they are extremely dependent on the type of ventilation system in place (natural or mechanical) and the type of heating system being used. Furthermore, well-functioning heat recovery systems also require good air-tightness in the buildings, which is something that is difficult to achieve in existing buildings. However, a qualitative analysis of the contribution of ventilation system improvements was performed. Household electricity was not included in the analysis.

Three types of measures were thus included in the analysis: temperature management measures, improved attic insulation and window replacement or refurbishment, and a combination of these (Table 11).
Table 11: Simulated scenarios

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reference case (22°C operative temperature all day long)</td>
</tr>
<tr>
<td></td>
<td><em>Temperature management</em></td>
</tr>
<tr>
<td>1</td>
<td>16°C 23–6h, 21°C rest of day</td>
</tr>
<tr>
<td>2</td>
<td>16°C 23–6h, 21°C 6–9h, 16°C 9–15h, 21°C 15–23h, 21°C 6-23h on weekends</td>
</tr>
<tr>
<td></td>
<td><em>Building envelope improvements</em></td>
</tr>
<tr>
<td>3a</td>
<td>Change windows to 3-pane energy saving windows (U = 0.7 W/m²,K)</td>
</tr>
<tr>
<td>3b</td>
<td>Renovate inner pane with low-emission pane (U = 1.4 W/m²,K)</td>
</tr>
<tr>
<td>4</td>
<td>Improve attic insulation (200–400 mm)</td>
</tr>
<tr>
<td>5</td>
<td>Combination of measures 2, 3a or 3b and 4 for ‘best results’</td>
</tr>
</tbody>
</table>

From the results for the individual buildings, the total savings potential at county level was calculated. The effect of more ambitious or less ambitious measures on total energy use was also determined.

Investment costs for building envelope improvements were retrieved from the annuities presented in [97], disregarding costs for operation and maintenance. Temperature management costs were estimated, allowing for calculation of total investment costs. Annuity factors, ANF, were then calculated for each measure in each building using the following equation:

$$ANF_{n,i} = \frac{(1 + i)^n i}{(1 + i)^n - 1}$$  \hspace{1cm} Eq. 3

where $n$ is the lifespan of each measure and $i$ the real discount rate. For the sake of simplicity, the real discount rate was set to 2%, following a recommendation by Philibert [99] to choose ‘the lowest foreseeable rate’ due to the uncertainty of future discount rates. Using a more complex approach that takes better account of future uncertainties, as proposed by Newell and Pizer [100], fell outside the scope of the analysis. Once the ANF were calculated, they were multiplied by the initial investment cost (Table 12) and divided by the annual energy savings to obtain the cost of the energy savings measure expressed in EUR/kWh. These input variables were then used to estimate total costs per building for the different measures and total costs for the entire county. Different interest rate levels were used in a sensitivity analysis. Furthermore, modelling results were compared to energy use values from the official energy statistics.
Table 12: Economic input variables for energy saving measures.

<table>
<thead>
<tr>
<th>Energy savings measure</th>
<th>Investment cost (EUR)</th>
<th>Unit</th>
<th>Lifespan (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature management</td>
<td>333</td>
<td>EUR/house</td>
<td>20</td>
</tr>
<tr>
<td>Attic insulation: approx. 200 mm</td>
<td>20</td>
<td>EUR/m²</td>
<td>40</td>
</tr>
<tr>
<td>Attic insulation: approx. 400 mm</td>
<td>29</td>
<td>EUR/m²</td>
<td>40</td>
</tr>
<tr>
<td>Insulation sloping roof</td>
<td>84</td>
<td>EUR/m²</td>
<td>40</td>
</tr>
<tr>
<td>Window renovation</td>
<td>288</td>
<td>EUR/m²</td>
<td>40</td>
</tr>
<tr>
<td>Window replacement</td>
<td>413</td>
<td>EUR/m²</td>
<td>40</td>
</tr>
</tbody>
</table>

5.3 Results

Energy use results differ substantially between the different sample houses, both in absolute figures and in energy load per square metre (see Table 13). As the energy load figures were larger than expected, they were validated with a manual calculation for sample house 3, which yielded very similar results. Scaling up the individual reference case energy use figures to county level, a total energy load of 1667 GWh per year is obtained for this part of the housing stock. As reported above, these houses account for 90% of the energy use among detached houses, which can be compared to the estimated figures for purchased energy in Chapter 4.3, which are in the range of 1600 GWh per year.

Table 13 also shows the savings (in per cent from the reference case) that can be achieved in the different scenarios. Temperature management has a relatively high potential of around 20% in the more ambitious scenario. Window replacement and renovation, on the other hand, did not yield large savings, except in the newer houses where effective windows are installed (and where other measures do not yield as much as in the older houses). Attic insulation has most potential in the oldest house and in sample houses 6 and 7, which are rather poorly insulated in the reference cases.

Savings in the ‘best combination’ scenario range from 29% in sample house 8 to 46% in sample house 7, averaging at 33%. Energy recovery from ventilation was not modelled specifically, but there should be further potential savings as ventilation losses account for 19 to 37% (25% on average) of total energy use in the sample houses.
Table 13: Sample house characteristics, energy load and savings potential and county level results

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Unit</th>
<th>County level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proportion of total stock of detached houses</strong></td>
<td>14.0</td>
<td>6.7</td>
<td>7.4</td>
<td>7.6</td>
<td>6.3</td>
<td>9.5</td>
<td>10.5</td>
<td>22.5</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td><strong>Reference case load</strong></td>
<td>48669</td>
<td>25636</td>
<td>51651</td>
<td>26171</td>
<td>26864</td>
<td>33665</td>
<td>21385</td>
<td>17050</td>
<td>kWh</td>
<td>1667 GWh</td>
</tr>
<tr>
<td>of which ventilation losses</td>
<td>27</td>
<td>24</td>
<td>19</td>
<td>25</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>37</td>
<td>%</td>
<td>24 %</td>
</tr>
<tr>
<td><strong>Specific energy load</strong></td>
<td>203</td>
<td>285</td>
<td>344</td>
<td>291</td>
<td>298</td>
<td>321</td>
<td>158</td>
<td>114</td>
<td>kWh/m²</td>
<td>216 kWh/m²</td>
</tr>
<tr>
<td><strong>Temperature management 1</strong></td>
<td>-15</td>
<td>-16</td>
<td>-15</td>
<td>-16</td>
<td>-16</td>
<td>-15</td>
<td>-17</td>
<td>-16</td>
<td>%</td>
<td>-16 %</td>
</tr>
<tr>
<td><strong>Temperature management 2</strong></td>
<td>-20</td>
<td>-21</td>
<td>-20</td>
<td>-20</td>
<td>-20</td>
<td>-20</td>
<td>-21</td>
<td>-21</td>
<td>%</td>
<td>-20 %</td>
</tr>
<tr>
<td><strong>Window renovation/replacement</strong></td>
<td>-7</td>
<td>-7</td>
<td>-5</td>
<td>-6</td>
<td>-6</td>
<td>-17</td>
<td>-11</td>
<td>-8</td>
<td>%</td>
<td>-8 %</td>
</tr>
<tr>
<td><strong>Attic insulation</strong></td>
<td>-10</td>
<td>-8</td>
<td>-7</td>
<td>-8</td>
<td>-9</td>
<td>-10</td>
<td>-15</td>
<td>-6</td>
<td>%</td>
<td>-9 %</td>
</tr>
<tr>
<td>‘Best combination’</td>
<td>-33</td>
<td>-33</td>
<td>-30</td>
<td>-32</td>
<td>-32</td>
<td>-32</td>
<td>-46</td>
<td>-29</td>
<td>%</td>
<td>-33 %</td>
</tr>
</tbody>
</table>
Cost calculations for the different scenarios show that temperature management is very cost-effective, with the measure cost being below 0.007 EUR per saved kWh in all cases (Figure 8). Window renovation or replacement on the other hand is the most expensive measure in sample houses 1 to 7, with the average cost being 0.072 EUR/kWh. Adding extra attic insulation is also quite cost effective in these houses, costing between 0.022 to 0.045 EUR/kWh. In sample house 8 window renovation is more expensive (0.15 EUR/kWh) as it already has rather efficient windows. Attic insulation is by far the most expensive measure in this house, as it has a sloping roof with little space to add extra insulation. The best combination of measures ranges from around 0.016 EUR/kWh in the older houses to 0.039 to 0.096 EUR/kWh in the two newer houses.

![Figure 8: Costs for energy efficiency measures per sample house in EUR per saved kWh.](image)

To check the robustness of the results and to reflect people’s supposed reluctance to implementing energy savings measures, different interest rates were tested for their effect on the cost of the best combination scenario (Table 14). The results show that cost levels would be around 0.1 EUR/kWh or below in sample houses 1 to 6 even with an extreme interest rate of 20%.
Table 14: Sensitivity analysis results for best combination of measures.

<table>
<thead>
<tr>
<th>Interest rate</th>
<th>Sample house</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>EUR/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td></td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5%</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td></td>
<td>0.06</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.11</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td>0.12</td>
<td>0.11</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
<td>0.21</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In total about EUR 400 million would have to be invested in the county to achieve the best combination savings, which corresponds to roughly EUR 6,200 per building to be refurbished or 8.2% of the disposable income in the county in 2008. The average cost per saved kWh is EUR 0.03.

5.4 Discussion

The eight sample houses are idealised in a number of ways (for better or worse) and the results from the simulations should be taken as indications of what is possible rather than as exact figures. One uncertainty is the modelling assumption that most houses have been maintained in their original shape. It is more likely that all houses have undergone at least some modifications with positive or negative effects on energy use. Attic insulation or ventilation systems may have been improved, while wall cavity insulation may have settled or doors may have warped, thereby decreasing wind tightness.

In general, however, it is likely that the savings potential is rather over- than underestimated. This can be illustrated by comparing model findings for energy load per square meter to data from the official statistics [72, 73], see Table 15. The discrepancy is rather large, with the modelled heat load requirements in some cases being more than twice as high as the figures for purchased energy from statistics. The main explanation for the difference is that the simulation software calculates the amount of thermal energy required to keep 22°C in the sample houses, while the official statistics only account for energy purchased for heating and hot water, thereby excluding for instance the “free” thermal energy used by heat pumps and without giving any information on indoor temperatures. Heat pumps being one of the main factors behind the discrepancy is confirmed by the above mentioned report from the Swedish Energy Agency, in which it is stated that half of the detached houses in Sweden are already equipped with some form of heat pump [21].
Table 15: Comparison between official statistics and model results.

<table>
<thead>
<tr>
<th>Sample house</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>Modelled energy need (incl. hot water)</td>
</tr>
<tr>
<td>Energy used according to official statistics 2008*</td>
</tr>
<tr>
<td>Energy used according to official statistics 2010*</td>
</tr>
</tbody>
</table>

*For Swedish average detached houses without non-residential areas [70, 71].

Ventilation is another factor that adds uncertainty. It is unlikely that natural ventilation turnover will be evenly distributed all year long as assumed by the Swedish National Board of Housing, Building and Planning [97]. During the cold season people might shut air inlets, thus decreasing heating requirements (and worsening indoor air quality). Furthermore, people may already choose to decrease indoor temperatures during the cold season, at least in some rooms. A more detailed zone modelling of the houses (with each room representing one separate thermal zone) could have provided additional insights into this problem area, and should be evaluated in future research. Finally, the sample houses were unable to catch the large variety in sizes and types of construction that exists in reality.

Another factor that might lead to an over-estimate of the savings potential is the way the simulation software handles temperature management. Indoor temperatures can be obtained on an hourly basis for all hours of the year. From these data, there appears that there is no lag in the heating system, instead temperatures are adjusted immediately (within the hour) to match the requirements set in the operating scheme for each building, see Figure 9. Despite the software provider assuring that the simulations are correct, the temperature profile should not be as sharp in reality, presumably leading to a somewhat higher energy use in the building. Furthermore, the temperature management scenarios are not realistic for every house in the county, due to the difference in lifestyles their occupants have. As mentioned above, dividing the sample houses into more detailed zones with different temperature requirements, would have improved the analysis. The findings for temperature management can also be compared to potentials observed in other studies. Gupta et al. [101] found that thermostat setbacks during nights and workdays can save 20-25% of the normal energy use (setting back temperatures to around 10°C), but they state that getting people to actually use their thermostats in this way is a challenge. Moon and Han [102] state
that thermostat setbacks can save up to 30% of energy use, based on a review of seven studies. Their own simulations of a setback from 22.2°C to 15.6°C show saving potentials of 20% for night time setback and 30% for night and daytime setback.

![Indoor temperature profile for one weekday in the sample houses.](image)

**Figure 9: Indoor temperature profile for one weekday in the sample houses.**

Regarding refurbishment costs, the results need to be treated with care. The costs considered here exclude all transaction costs and other costs that might make the investments less likely to materialise in reality. Thus, the cost estimates should be taken as an indicator for the magnitude of the challenge the county is facing, rather than exact figures. Furthermore, it needs to be kept in mind that costs are just one of many factors that govern the implementation of energy savings measures, as thoroughly illustrated by for instance Stern [46] and McKenzie-Mohr [45].

With these limitations in mind, the costs for the proposed refurbishment measures are surprisingly low, given that they can be implemented gradually during four decades, for the long-term energy efficiency targets are to be met.

Still, the lesson is that neither technology nor money should be the main barriers to achieving substantial energy savings, although of course transaction and other costs have to be added to reflect the real cost of implementing the measures.
5.5 Conclusions

Despite the uncertainties involved, the conclusion can be drawn that energy savings of about 30% can be achieved with simple means and at a reasonable cost, without endangering the cultural heritage in the building stock. This is in line with findings from Nemry et al. [103], who confirm that the greatest savings potential is to be found in detached houses in Europe and that large savings can be achieved with cost-effective means. However, the 50% reduction in energy use aimed for by the County Administrative Board will not be achieved by the measures analysed in this chapter, especially if potential rebound effects are taken into account. Furthermore, many houses will have to decrease their energy use by far more than 50%, since there will be many buildings that for technical, economic or other reasons will not come close to cutting their energy use in half. This calls for a deeper exploration of the possibilities to reduce energy use in existing buildings beyond 50%.
6. Energy Savings Beyond 50% - Two Swedish Examples

6.1 Introduction

As was shown in the previous chapter relatively far-reaching savings can be achieved with “conventional” [104] refurbishment methods in existing single detached houses. However, in many buildings, in particular those that are exempt from the requirements in the EPBD (see Chapter 2) such as buildings with high cultural values, not even these simple measures will be able to be carried out. Therefore savings must reach beyond 50% in each refurbishment that is carried out, if the 50% energy savings target is to be realised until 2050. Rysanek and Choudhary [104] state that these “deep-energy retrofits” are “large-scale refurbishments that make significant alterations to a building’s architectural design, componentry, and operations towards effecting major energy savings (upwards of 50%)”. This chapter presents one single detached house for which this statement is true, and one where savings upwards of 50% are achieved with neither “significant alterations” nor “conventional” thinking. The aim is to illustrate two alternative pathways for achieving lower energy use in privately owned buildings. One of the houses, Hälsingbo, is refurbished cost-efficiently, however the occupants are required to engage actively and continuously in maintaining the indoor climate. The other house, Finnängen, is refurbished according to the passive house standard and also equipped with solar PV-system, solar thermal system and ground source heat pump for automatic operation. In economic terms Finnängen represents a high investment solution for energy efficiency that supplies a well-functioning indoor environment automatically. In Hälsingbo, care must be taken by the residents to ensure thermal comfort energy efficiently.

The two houses were selected because they were the only ones in Sweden known to the author (who is also the owner of Hälsingbo) in the initial stages of the study, where savings beyond 50% had been achieved. Even as late as in October 2013, only three deep refurbishment projects of detached houses were identified in a national survey [105], one of them being Finnängen.
6.2 Site Description: Hälsingbo

Hälsingbo is located in southern Dalarna in central Sweden, about 200 km northwest of Stockholm at an altitude of 156 m above sea level. The annual mean temperature in nearby Stjärnsund for 1961-1990 was 4.3°C and ranges from an average of -6.4°C in January to 15.6°C in July [106]. The house was originally constructed in the 1850s with roundwood timber with a diameter of ca. 20 cm. In the late 1920s, the second floor was added using a wood frame construction and the house underwent extensive refurbishment in 1954, and again in the early 2000s. The heated area was then 91 m² (based on measurements according to Swedish Standard 02 10 53). When the property was purchased in 2007 by the current owners, there was one cast-iron fireplace (η≈40%) in the living room and all rooms were heated with direct current electric heaters. The original insulation was still in place in most parts of the building, consisting of wood chip insulation in the floors and thin (3 cm) mineral wool “pillows” in some of the walls that had been refurbished in 1954. The south-eastern gable was insulated with modern 5 cm mineral wool. Most doors had warped and constantly leaked air. All windows were of traditional 2-pane type (U=2.8 W/m²K) and had not been draught-proofed. Had the house been permanently occupied, it would have had a heat demand of 14,300 to 17,400 kWh per year, according to reference values [107]. The previous owners used about 8,500 kWh of electricity and an unspecified amount of firewood. The house was occupied four days per week on average by the previous owners according to themselves. The house was used as a leisure home from 2007 to mid-2009. The house has been permanently occupied since then, first by two adults and since mid-2011 by two adults and a child.

6.3 Site Description: Finnängen

Finnängen is located outside the city of Linköping, ca. 200 km southwest of Stockholm at an altitude of 67 m above sea level. The annual mean temperature in Linköping for 1961-1990 is 6.8°C and ranges from an average of -3.0°C in February to 17.0°C in July [106]. The house was originally constructed in 1976 with a heated space area of 212 m² on one floor with a heated basement. The property was purchased by the current owners in 2009. Annual energy use amounted to 30,000 kWh of pellets for heating (with radiators) and 5,000 kWh for hot water. Electricity use amounted to 5,000 kWh, of which 4,000 kWh were used for household electricity and 1,000 kWh for building operation electricity. A mechanical ventilation system was in place when the house was purchased. Infiltration was measured to 800 l/s at 50Pa (300m²)=2.67 l/s,m².
U-values for important building components were calculated, see Table 16 below.

*Table 16: U-values at Finnängen prior to refurbishment.*

<table>
<thead>
<tr>
<th>Component</th>
<th>U value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>0.40</td>
</tr>
<tr>
<td>Roof</td>
<td>0.32</td>
</tr>
<tr>
<td>Basement</td>
<td>0.6/1.6*</td>
</tr>
<tr>
<td>Windows</td>
<td>3.00</td>
</tr>
</tbody>
</table>

*The basement consists of two sections with different insulation values.*

The house had a typical Swedish 1970s exterior finish, see Figure 10.

*Figure 10: Finnängen prior to refurbishment.*

6.4 Method

6.4.1 Objectives, Strategies, Criteria

Hälsingbo

For the refurbishment process of Hälsingbo, clear objectives were set in early 2009, before the owners moved into the house permanently. The objectives were based on an insight that climate change, resource depletion, general environmental degradation and subsequent economic decline are likely to create a more decentralised and small-scale society, where industrial and high-tech products may be less readily available. The overall objective was to enable a high-quality life for both the current and future...
occupants, no matter in which direction society will evolve. More specifically the objectives were stated as follows:

- Keep overall monthly expenses as low as possible to decrease the need for wage labour,
- Take no loans,
- Use locally sourced (and recycled) materials to an as large a degree as possible,
- Only use materials non-hazardous to human health,
- Make the house easy to maintain and operate,
- Use technology that can be understood, maintained and replaced by non-experts,
- Create a beautiful home.

Setting the objectives formed the first step in a six step design cycle that was used throughout the entire refurbishment process, see Figure 11. The design cycle is modified from the design process commonly used in permaculture design, (see for instance [108-110]) and can be compared to the more complex refurbishment approach for larger-scale projects as presented by Ma et al. [111].

Once the objectives were set, surveying was initiated. This involved surveying the house itself, i.e. its physical characteristics, the performance of the different components of the house such as windows, doors, heaters etc., how the house reacts to different weather conditions and how the house is affected by the four seasons. But the survey also included observing the residents’ interaction with the house throughout the entire year, their needs and desires regarding comfort and standard, the tools and appliances they use in their daily life and so on.

The survey results were analysed in the third step and based on the findings improvements were designed. How the design was done depended very much on the solutions chosen, but building ecology (e.g. [112]) and techniques used in building preservation were the main sources of inspiration. The design phase was used to unite the objectives for the refurbishment process with the preconditions for the site that were identified during the survey, with the aim to realise as much as possible of the potential the site has.

Once the improvements were designed, the implementation phase started, followed by an evaluation of the changes made. During the entire design process, a cycle of observation, reflection and reviewing was carried out to ensure that appropriate choices were made. Thus, the design process used is iterative. One principle that guided the entire process was that “small steps make small mistakes”, mainly to avoid lock-in effects that can occur with large investments, and to allow for a continuous learning process. The process has been used continuously since 2009 for the entire refurbishment and is meant to go on indefinitely, although the aim is to more and more reduce the time spent on refurbishment in favour of time for other activities.
Figure 11: Design cycle used in the Hälsingbo refurbishment process.
Finnängen
For the case of Finnängen a deep energy refurbishment was aimed for. The refurbishment was conducted in one intensive go, but the owners were able to continue living in the house. The main objective was to reach a very low energy use while maintaining a good and healthy indoor climate. Other objectives were:

- Achieve a net energy surplus through the use of photovoltaics (PV) and solar thermal,
- Refurbish a home in an attractive way and at the same time find a way of deep energy refurbishment that would correspond to “market” demands.
- Create an annex building with “outdoor feeling” to replace the existing, electrically heated conservatory.
- Achieve passive house standard.
- Minimise lifecycle energy use.
- Test new technologies such as a newly developed heat pump solution and special designed photovoltaic modules
- Make energy use as independent as possible from user practices.

Regarding strategy, many technical as well as aesthetical solutions were designed by the owners themselves, while most of the actual refurbishment was conducted with paid labourers. Furthermore, a professional consultant was hired to ensure that air-tightness and moisture properties of building components were able to meet building codes and passive house standards.

Two criteria that were set for the system were to limit total electricity consumption to 7,000 kWh/year and design the PV system to produce approximately 9,000 kWh/year.
6.4.2 Data Collection

Data collection was performed by the house owners themselves.

**Hälsingbo**

The annual firewood requirements were based on estimates from the amount of fuel purchased every year. The input parameters are presented in Table 17 below. The firewood purchased consists of a mix of birch and fir tree wood in equal proportions, which yields a heating value of 904 kWh per m$^3$ of loose wood.

*Table 17: Input parameters for calculation of heat use from fire wood. Based on [113] and [114].*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion loose/solid cubic meter</td>
<td>2.8</td>
<td>m$^3$ loose/m$^3$ solid</td>
</tr>
<tr>
<td>Heating value fir</td>
<td>2200</td>
<td>kWh/m$^3$ solid</td>
</tr>
<tr>
<td>Heating value birch</td>
<td>2820</td>
<td>kWh/m$^3$ solid</td>
</tr>
<tr>
<td>Heating value mix (50/50)</td>
<td>904</td>
<td>kWh/m$^3$ loose</td>
</tr>
</tbody>
</table>

The heating season starts typically in September and ends in April. Monthly data were not collected, but naturally wood consumption is at its highest during the coldest months, usually January and February with mean monthly temperatures of -6.4°C and -6.1°C respectively for the period of 1961 to 1990 [106].

Figures for electricity use are entirely based on monthly data collected from the electricity supplier. However electricity is used for both hot water, household electricity and to a limited extent space heating. These cannot be distinguished from the electricity statistics provided by the supplier. Therefore electricity use of most loads in the household was either measured or estimated in the first half of 2010. The cost of electricity purchased is given in Table 18 below and can be compared to Swedish and European (EU-27) domestic consumer electricity prices that averaged EUR 0.204/kWh in 2011 and EUR 0.184/kWh respectively [115].

*Table 18: Cost of electricity (figures for May 2013).*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual network fee</td>
<td>209</td>
<td>EUR/year</td>
</tr>
<tr>
<td>Variable network fee</td>
<td>0.028</td>
<td>EUR/kWh</td>
</tr>
<tr>
<td>Wind power electricity</td>
<td>0.073</td>
<td>EUR/kWh</td>
</tr>
<tr>
<td><strong>Total</strong>*</td>
<td>0.24</td>
<td>EUR/kWh</td>
</tr>
</tbody>
</table>

*Based on a total consumption of 1500 kWh/year
**Finnängen**

Electricity production from the PV panels is metered continuously as is electricity consumption. The electricity use of the heat pump is metered separately. Temperatures are logged at two points in the house, one upstairs and one in the basement. Heat production from solar thermal is not measured, but total water use is used as an indicator for hot water use.

### 6.4.3 Building Simulations

Simulations in the simulation software IDA ICE 4.101 of both houses were performed to improve understanding of how the houses would perform under different comfort levels, i.e. to illustrate how user behaviour affects the total energy use in the houses. Both houses were simulated for three different comfort levels, using Linköping climate data as an input:

- **Standard temperature level:** All rooms have an air temperature of at least 20°C.
- **Low temperature level:** Rooms have same air temperatures as in Hälsingbo, simulated as 13 to 16°C on average to reflect the use of different climate zones in the house.
- **High temperature level:** Rooms have an air temperature of at least 24°C.

Finnängen (Figure 12) was modelled as a three zones model in the software with upper floor, lower floor and the octagonal shaped annex as separate zones. Each zone has one person present constantly which is an approximation for a family of two adults with three children, a cat and a dog. In total, the zones have internal heat gains from equipment summing up to 4000 kWh/year. The model was then compared to measured values on an annual basis for validation.

![Figure 12: Finnängen – Photograph and model in IDA](image)

Hälsingbo, (Figure 13), was modelled as a two zones model, one for the upper floor and one for the lower, with scheduled temperature set points between 13 and 16°C. This is a simplification of the actual fact that the house used separate climatic zones for each room but fits for comparison in this case. The average modelled air temperature during the heating season (October to April) is 17 °C, with variations between 13-20 °C. The upper
zone and lower zone have an equal distribution of internal heat gains from two people present and equipment gains summing up to 1200 kWh/year.

Figure 13: Hälsingbo – Photograph and model in IDA

Table 19 below summarises some of the basic input data that were used in the simulation software. Total floor area for the houses are actual areas, while the areas given in the site description are the areas that are used for taxation and energy statistics purposes. SHGC is the solar heat gain coefficient for the windows and ACH is the number of air changes per hour in the buildings.

Table 19: Basic simulation in data for the two houses.

<table>
<thead>
<tr>
<th></th>
<th>Finnängen</th>
<th>Hälsingbo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total floor area</td>
<td>253 m²</td>
<td>135 m²</td>
</tr>
<tr>
<td>Total heated volume</td>
<td>599 m³</td>
<td>299 m³</td>
</tr>
<tr>
<td>Ceiling height, lower floor</td>
<td>2.2 m</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Ceiling height, upper floor</td>
<td>2.4 m</td>
<td>2.1 m</td>
</tr>
<tr>
<td>Average U-value</td>
<td>0.26 W/m² K</td>
<td>0.46 W/m² K</td>
</tr>
<tr>
<td>Total specific heat loss (Q_{tot})</td>
<td>150 W/K</td>
<td>143 W/K</td>
</tr>
<tr>
<td>Air flow rate (forced, kitchen fan)</td>
<td>45 (100) l/s -</td>
<td>-</td>
</tr>
<tr>
<td>Ventilation heat recovery efficiency</td>
<td>81%</td>
<td>-</td>
</tr>
<tr>
<td>Window SHGC</td>
<td>0.47</td>
<td>0.76</td>
</tr>
<tr>
<td>Air tightness</td>
<td>0.6 ACH</td>
<td>1.5 ACH</td>
</tr>
<tr>
<td>Geographical situation</td>
<td>Lat 58°31’</td>
<td>Lat 60°26’</td>
</tr>
<tr>
<td></td>
<td>Long 15°30’</td>
<td>Long 16°11’</td>
</tr>
</tbody>
</table>

Modelled U-values\(^8\) and their associated input parameters are given in Table 20. The frame fraction is the share of frame of the total window area.

---

\(^8\) The total loss term include transmission losses, ventilation losses and infiltration losses. The latter amount to 8 W/K for both cases.

\(^9\) The modelled U-values can be compared to the requirements set in the building codes, see Table 3. Hälsingbo would thus not comply with the required minimum values after refurbishment.
Table 20: Modelled U-value for components and walls.

<table>
<thead>
<tr>
<th>Construction</th>
<th>Modelled $U$-value [W/m²,K]</th>
<th>Thickness [m]</th>
<th>Area [m²]</th>
<th>Frame fraction</th>
<th>SHGC</th>
<th>$U_A$ [W/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Finnängen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td>0.09-0.10</td>
<td>0.5</td>
<td>209</td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Ground new</td>
<td>0.12</td>
<td>0.4</td>
<td>28</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Ground old</td>
<td>0.4</td>
<td>0.2</td>
<td>112</td>
<td></td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>Roof</td>
<td>0.08</td>
<td>0.50</td>
<td>140</td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Windows</td>
<td>0.77</td>
<td>0.1</td>
<td>51</td>
<td>0.3</td>
<td>0.47</td>
<td>39</td>
</tr>
<tr>
<td>Thermal Bridges</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>142</strong></td>
</tr>
<tr>
<td><strong>Hälsingbo</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td>0.41</td>
<td>0.1-0.3</td>
<td>145</td>
<td></td>
<td></td>
<td>59</td>
</tr>
<tr>
<td>Ground floor &amp; Ground</td>
<td>0.15</td>
<td>0.4</td>
<td>67</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Roof</td>
<td>0.24</td>
<td>0.25</td>
<td>67</td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Windows</td>
<td>2.8</td>
<td>0.1</td>
<td>14</td>
<td>0.3</td>
<td>0.76</td>
<td>39</td>
</tr>
<tr>
<td>Thermal Bridges</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>133</strong></td>
</tr>
</tbody>
</table>
6.5 Results

6.5.1 Hälsingbo

Heating
Since the chosen design process is intended to go on indefinitely, there is no end-result to be presented here. However, quite tangible results have been achieved since the initiation of the refurbishment process in mid-2009.

Lack of insulation was quickly identified as an area to focus on. In connection with a few minor refurbishments, some of the exterior walls were insulated with sheep’s wool in 2009. The largest intervention so far, however, was the complete refurbishment of the upper floor. The original wood shavings insulation was replaced by 20 to 25 cm of flax insulation and the original three small rooms with very low ceiling were replaced by two larger ones with more head space. The wall between the two rooms was insulated with 10 cm flax insulation, to create two individual temperature zones.

Excess infiltration was another area that was addressed initially. All windows were draught-proofed in 2009 and the outside doors (which had warped severely) were replaced entirely by new doors insulated with 5 cm expanded polystyrene insulation. Clay plaster was used on the inside of most exterior walls for air-tightening and improvement of indoor climate.

Another major change was the successive removal of the existing direct electrical current heating system. This led to a reduction of the heated area by 91 m$^2$ to 74 m$^2$, as the entrance hallway and staircase were left without heating system. A new heating system was slowly introduced between 2009 and 2012, starting with the wood stove ($\eta$ approx. 40%) in the kitchen that was installed in July 2009. A 2.5 kW wood-fired masonry heater ($\eta=80\%$) was installed in one of the bedrooms in 2010. A large 5 kW masonry heater ($\eta=80\%$) was installed in the living room in 2012 and another 2.8 kW masonry heater ($\eta=80\%$) was constructed in the second bedroom in late 2012, see Figure 14. Electric heating (with movable radiators) is now only used during longer periods of absence from the house, to prevent water pipes from freezing.
One pattern that manifested itself was that the area used in the house changed between seasons. In the winter of 2009/2010, the residents only used kitchen and living room, thus reducing the area actually heated to 43 m$^2$. From 2010 onwards, only one of the bedrooms has been used during the winter.

Insulation improvements, draught-proofing, clay plastering and conversion of the heating system from electricity to wood, coupled with behavioural adaptation to temperature conditions have led to substantial decreases in energy use for heating in the house. Firewood use has been averaging 6 m$^3$ of loose wood, consisting of 50% birch and 50% fir. Using the figures in Table 17, this yields a total energy use of about 5,400 kWh/year. To this can be added an estimated electricity use of about 300 kWh/year for the electric radiators.

**Hot water**
The existing electric hot water boiler has not been replaced so far. Observations of hot water use over time (see Table 21) revealed that none of the alternatives (solar thermal, wood-fired boiler) would have been profitable. Furthermore, rebound effects were likely to occur, i.e. installing a solar thermal system would probably lead to higher hot water use even in winter time when the sun does not contribute. It needs to be mentioned, too, that some of the hot water use is externalised to the public bathhouse in the
closest village, which is used once a week from September to May. Total electricity use for hot water is thus estimated to roughly 450 kWh/year.

*Table 21: Estimated hot water use and corresponding electricity consumption*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water use</td>
<td>8350</td>
<td>l/year</td>
<td></td>
</tr>
<tr>
<td>Temperature hot water</td>
<td>45</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Temperature cold water</td>
<td>6</td>
<td>°C</td>
<td>From deep well, varies through the year</td>
</tr>
<tr>
<td>Electricity use for hot water</td>
<td>454</td>
<td>kWh/year</td>
<td>Includes estimated 20% boiler losses</td>
</tr>
</tbody>
</table>

Summing up energy use for heating and hot water yields 6,150 kWh per year (5,400 kWh from wood and 750 kWh from electricity). This can be compared to the average annual energy use in comparable houses of 14,300 to 17,400 kWh [107], which corresponds to savings of 8,150 to 11,250 kWh per year (57 to 65% savings).

The specific energy use for heating, which is a much used unit in Sweden despite its many drawbacks, amounts to 83 kWh/m²/year. This is 25% lower than the requirements for construction of new buildings set in the building codes (cf. Table 1).

**Household and operating electricity**

The continuous improvement cycle was also applied on the use of household electricity. The most significant savings were achieved for cooling and lighting. Regarding cooling, the freezer was never put to use, thus saving an estimated 400 kWh per year [30]. The fridge was originally located in the kitchen. In 2009, an existing cupboard ventilated with outside air, was insulated and replaced the fridge from late September or early October to mid-April. To save space and to reduce heat losses to the kitchen, the fridge was then moved to the unheated pantry in the north-eastern corner of the house, which reduced electricity use for the fridge further, probably saving 100 kWh per year or more [30].

With respect to lighting, strict rules were introduced to the family to only have the lights turned on that are actually needed (something that goes against Swedish cultural practice, see [116] for a comparison of energy use for lighting with other European countries). From that base, observations were made on the actual amount of time each lamp in the house was switched on. The lamps used the most were replaced by LED-lamps, which included all lamps in the living room and kitchen. Lamps used often were replaced with CFLs and the lamps used the least (but which needed to give full light immediately) were kept as they were. This included lamps in the pantry and on the attic.
Another focus area was the use of electric kitchen and woodworking tools. Initially, only hand tools were used in the refurbishment, but eventually a few power tools were bought to speed up the building process. Regarding kitchen tools, all devices used are mechanical, including a hand-cranked flour mill and oat meal press. The only exception is a blender, for which no satisfying manual replacement could be found. Other electric appliances in use are the electric stove used during the summer (replaced by the wood stove in winter time), a hot water boiler, a vacuum cleaner and a washing machine.

Standby losses were minimised through the use of multi-plug connectors with switch for the computers and the modem.

Total household electricity use is estimated to about 750 kWh/year, of which 200 kWh are used for computers and modems, 100 kWh for lighting, 60 kWh for refrigeration, 50 kWh for laundry and 340 kWh for other uses. These figures can be compared to household electricity use in average Swedish single-family homes which is thought to amount to 4,000 to 6,300 kWh/year [72].

Table 22: Use of household electricity per type of load.

<table>
<thead>
<tr>
<th>Type of use</th>
<th>Electricity use (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computers/modem</td>
<td>200</td>
</tr>
<tr>
<td>Lighting</td>
<td>100</td>
</tr>
<tr>
<td>Cooling</td>
<td>60</td>
</tr>
<tr>
<td>Laundry</td>
<td>50</td>
</tr>
<tr>
<td>Other*</td>
<td>340</td>
</tr>
<tr>
<td>Total</td>
<td>750</td>
</tr>
</tbody>
</table>

*Cooking, appliances, power tools, water pump, motor heater

Overall electricity use results

Use of electricity has been ranging from 1190 kWh/year to 2171 kWh/year during the period 2009-2013 (see Figure 15), with the average consumption amounting to about 1500 kWh/year. Of this, 300 kWh/year can be accounted to the use of electric radiators during longer spells of absence from the house and 450 kWh/year to hot water use. The remaining 750 kWh/year are as stated previously used for lighting, cooking, appliances, pumping drinking water from the well into the house, power tools and a motor heater that is used occasionally for the car.
Figure 15: Annual electricity use 2009-to 2013. Figure for 2013 is estimated by the electricity provider.

Monthly electricity use data reveal that the extreme electricity use for 2010 can be explained by excess use in January to April. This was due to a fireplace being broken in January and February (with temperatures as low as -30°C during the period). Furthermore one of the original electric heaters that had not been removed at that time had been switched on accidentally in a room that was not in use. The somewhat higher electricity use in February and March 2013 can be explained by two five-day periods of absence from the house when outdoor temperatures ranged from -10 to -20°C.

Figure 16: Electricity use per month from 2009.
Economy

The combination of taking small steps at a time in the refurbishment process and using what was deemed “appropriate” technology (cf. [117]) to reduce energy use were key to keeping monthly expenses low. Furthermore, most refurbishment projects were conducted by the occupants (and their friends and relatives) themselves. Costs for paid labour amounted to no more than EUR 1,600 for the entire refurbishment, and none of this was directly connected to the energy performance of the house. On the demand side, replacement of the exterior doors and insulation of the roof were most expensive, see Table 23. Other measures, such as draught-proofing, insulating hot water pipes and replacement of light sources amounted to a total of EUR 550. Supply side measures included the masonry heaters and the purchase of wind power shares, which allow the occupants to purchase wind power electricity at production cost and which yields a low and predictable annual electricity cost. Total energy-related investment costs amounted to roughly EUR 10,000.

Table 23: Investments from January 2009 to June 2013.

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Investment cost (EUR)</th>
<th>Expected service life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doors</td>
<td>3,300</td>
<td>100</td>
</tr>
<tr>
<td>Insulation</td>
<td>2,800</td>
<td>40</td>
</tr>
<tr>
<td>Other measures</td>
<td>550</td>
<td>40</td>
</tr>
<tr>
<td>Masonry heaters</td>
<td>2,000</td>
<td>40</td>
</tr>
<tr>
<td>Wind power shares</td>
<td>1,300</td>
<td>20</td>
</tr>
</tbody>
</table>

Annual heating costs amount to EUR 470 while annual household electricity costs are EUR 110. The annual energy cost of the house corresponds to approximately 45 hours of wage labour at current salaries for the occupants, or 1.8 hours per month and adult.

Table 24: Annual heating and electricity costs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual heating costs*</td>
<td>470</td>
</tr>
<tr>
<td>Annual household electricity cost</td>
<td>110</td>
</tr>
</tbody>
</table>

*including cost for firewood, electric heating and hot water
6.5.2 Finnängen

The refurbishment process at Finnängen was finished in late 2010 and the results presented below are based on measurements from 2011-2012.

**Heating and hot water**

Heat demand was reduced by improvement of the entire thermal envelope of the house. The facades were insulated with 230 mm extruded polystyrene with graphite\(^{10}\) content (EPSG) \((\lambda=0.031\ \text{W/mK})\), the basement with 220 EPSG and 30 mm extruded polystyrene (EPS, \(\lambda=0.036\ \text{W/mK}\)) while the roof was insulated with 300 mm EPSG on the northern side and with 200 mm EPS \((\lambda=0.033\ \text{W/mK})\) on the southern side. All windows were replaced with low-energy windows with a total U value of 0.77 W/m\(^2\)K. Total floor space was increased through an annex to the south with a floor area of 34 m\(^2\), see Figure 17. The annex was insulated with 500 mm EPSG in the ceiling, 400 mm graphite in the walls and 320 mm EPS \((\lambda= 0.033\ \text{W/mK})\) in the foundation. The entire construction was air-tightened from the outside with a latex air-tightening membrane, yielding an air-tightness value of 0.13 l/s,m\(^2\).

The pellet-based heating system was replaced with a ground source heat pump, but the radiators were maintained. The floor heating system was expanded in the refurbishment. Furthermore, a ventilation heat recovery system was installed. The improvements made resulted in a decrease in space heating demand by 30,000 kWh to 10,000 kWh/year, see Figure 18. The heat pump uses 3,000 kWh of electricity annually for both space heating and hot water.

![Figure 17: Finnängen after the refurbishment.](image)

Hot water use remained at its original level of roughly 5000 kWh per year (Figure 18) prior to the refurbishment, but is now supplied by solar thermal (from May to September, with some contribution from February onwards) and heat from the heat pump. The specific energy use for heating and hot water.

\(^{10}\) The graphite in the material reduces radiation losses.
water amounts to 61 kWh/m$^2$, which can be compared to the requirements on (electrically heated) new houses in the same climate zone of 55 kWh/m$^2$, year. However, given the fact that only purchased energy is attributed to the energy use, which amounts to 1900 kWh/year to cover heat demand during the darkest months, the specific energy use at Finnängen according to Swedish energy accounting principles is as low as 7.8 kWh/m$^2$, year.

![Figure 18: Monthly energy use for space heating and hot water and total annual energy use at Finnängen.](image)

**Household and operating electricity**

Household electricity use decreased with 1,000 kWh per year to 3,000 kWh per year after the refurbishment. This was mainly achieved through A-classed appliances, and low-energy lighting. Standby-losses were decreased through multi-plug connectors with switch. Building operation electricity use remained constant, but is now distributed among other sources than prior to the refurbishment, e.g. both supply and exhaust air and also heat recovery as well as the solar thermal circuit. Much of the annual electricity use is covered by electricity from solar PV panels which were installed on the south-facing side of the roof during the refurbishment. The solar cells produce about 9,000 kWh per year, which yields a net surplus of 2,000 kWh annually. The monthly electricity use and production profile is shown in Figure 19. As becomes clear, the heating season starts in late September and ends in late April. Electricity needs to be purchased from October to March, while a surplus is generated from April to September. The overall annual electricity balance is shown in Figure 20.
Figure 19: Monthly electricity use and production profile for Finnägen (2012).

Figure 20: Annual electricity balance at Finnägen (2012).
Economy

Energy-related investment costs and the expected service life of the different investments made are shown in Table 25 below. On the demand side, window replacement in the entire building (including replacing the basement windows with much larger ones) was the largest investment, followed by insulation improvement, draught-proofing and installation of the ventilation heat recovery unit. On the supply side, the solar PV system cost EUR 18,000, followed by the solar thermal system and the heat pump, yielding a total cost of about EUR 58,000 for the entire energy refurbishment package.

Table 25: Energy-related investments at Finnängen.

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Investment cost (EUR)</th>
<th>Expected service life(years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draught-proofing</td>
<td>5,600</td>
<td>40</td>
</tr>
<tr>
<td>Window replacement</td>
<td>11,000</td>
<td>40</td>
</tr>
<tr>
<td>Insulation</td>
<td>8,300</td>
<td>40</td>
</tr>
<tr>
<td>Ventilation heat recovery unit (HRX)</td>
<td>1,700</td>
<td>10</td>
</tr>
<tr>
<td>Ventilation heat recovery labour</td>
<td>3,900</td>
<td>40</td>
</tr>
<tr>
<td>Solar PV</td>
<td>18,000</td>
<td>40</td>
</tr>
<tr>
<td>Solar thermal (incl. storage tank)</td>
<td>6,700</td>
<td>40</td>
</tr>
<tr>
<td>Heat pump</td>
<td>2,800</td>
<td>20</td>
</tr>
</tbody>
</table>

Although a net electricity surplus is produced, some electricity has to be purchased nevertheless (see Figure 19). This is due to the fact that monthly net metering is employed, as opposed to annual net metering, which would yield different results (see [118] for details on different metering methods). Annual electricity costs amount to EUR 200.

6.5.3 Comparison

Table 26 below shows a comparison of the two cases. The $U_A$ value is based on input data to the simulation software. The annual energy costs presented in the table include the use of household electricity. The net present value (NPV) of the investments and annual energy costs were calculated with both a 2% and a 6% real interest rate and a 40 years life span. Hälsingbo has a higher specific energy use, although total energy use is much lower that at Finnängen, which indicates a potential shortcoming in Swedish legal
requirements as regards specific energy use as the main variable for evaluating the energy performance of a building.

Table 26: Comparison of energy use and economic results for the two cases.

<table>
<thead>
<tr>
<th></th>
<th>Hälsingbo</th>
<th>Finnängen</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_A$ value (W/K)</td>
<td>133</td>
<td>142</td>
</tr>
<tr>
<td>Net heat demand (kWh/year), incl. hot water</td>
<td>6,150</td>
<td>15,000</td>
</tr>
<tr>
<td>Saved energy for heating and hot water (kWh/year)</td>
<td>9,700*</td>
<td>20,000</td>
</tr>
<tr>
<td>Net household electricity demand (kWh/year)</td>
<td>750</td>
<td>3,000</td>
</tr>
<tr>
<td>Purchased energy (kWh/year)</td>
<td>6,900</td>
<td>2,300</td>
</tr>
<tr>
<td>Specific energy use (kWh/m², year)</td>
<td>83</td>
<td>61**</td>
</tr>
<tr>
<td>Total investment cost (EUR)</td>
<td>10,000</td>
<td>58,000</td>
</tr>
<tr>
<td>Annual energy cost (EUR)</td>
<td>580</td>
<td>200</td>
</tr>
<tr>
<td>NPV at 2% real interest (EUR)</td>
<td>26,500</td>
<td>67,000</td>
</tr>
<tr>
<td>NPV at 6% real interest (EUR)</td>
<td>18,500</td>
<td>60,000</td>
</tr>
<tr>
<td>Cost of energy savings (EUR/kWh)</td>
<td>0.020</td>
<td>0.062</td>
</tr>
</tbody>
</table>

*average between lowest and highest savings from reference.  
**7.8 kWh/m², year if disregarding energy use covered by solar energy.
6.5.4 Simulation Results

For each of the three scenarios simulated, monthly and annual net heat load figures were obtained for both houses. The monthly results for Hälsingbo are shown in Figure 21. The scenario marked 13-16°C is intended to represent the current energy use profile.

![Figure 21: Monthly heat load for Hälsingbo for the three temperature scenarios.](image1)

The total annual heat load figures (Figure 22) reveal that the simulated figures in the low temperature scenario are somewhat higher than the actually observed energy use of 5,700 kWh per year for heating. Under the 20°C scenario the heat load increases by almost 70% to roughly 10,000 kWh per year. In the high temperature scenario the heat load increases by 135% to about 14,000 kWh per year.

![Figure 22: Total annual heat load for Hälsingbo.](image2)
The monthly heat load results for Finnängen are shown in Figure 23. The currently used temperature profile is between the 20°C and the 24°C scenario.

![Figure 23: Monthly heat load for Finnängen for the three temperature scenarios.](image)

The total annual heat loads (Figure 24) show that a temperature regime similar to that currently used at Hälsingbo would decrease the total heat load by 50% from today’s value to approximately 5,000 kWh per year. Even a 20°C temperature scenario would imply savings compared to today’s level, with a total annual heat load of about 7,200 kWh, which corresponds to a 44% increase from the low temperature scenario. Increasing the operating temperature to 24°C would imply a 130% increase in heat load from the low temperature scenario, but only a slight increase from the current annual heat load.

![Figure 24: Total annual heat load for Finnängen.](image)
6.6 Discussion

The two Swedish case studies presented in this chapter illustrate two altogether different approaches to reaching the 50% energy savings target and beyond. They can be seen as extreme cases on opposite ends of the scale of approaches towards energy efficiency.

Finnängen is the case that is probably more compatible with the current discourse on energy use and societal progress. It requires high investment (and therefore supports economic growth and creates jobs), but as the simulation results show, it is not as immune to different user behaviour as was aimed for by the owners. It requires access to investment capital and probably also a strong interest in technical issues from the occupants. It also entails significant alterations to the exterior of the building, and conflicts therefore with the preservation of architectural and cultural values. From a wider perspective, the approach requires a functioning, specialised and globalised large-scale economy in order to provide the high-tech materials and components to keep the house functioning over the coming decades.

The approach used in Hälsingbo on the other hand is far from the mainstream way of dealing with energy efficiency and would fall into the realm of the concept of “Voluntary Simplicity”, that has been defined as “the degree to which an individual selects a lifestyle intended to maximize his/her direct control over daily activities and to minimize his/her consumption and dependency” [119]. It requires the continuous input of physical labour (chopping, stacking and carrying firewood, as well as lighting fires every day in up to five different fireplaces), something that is hardly compatible with how most people currently live their lives in Sweden. The approach also requires high awareness of the energy impact of each action one performs in the house, as the house is more sensible to user behaviour than Finnängen. However, the system has an extremely low life-cycle cost, and actually enables the occupants to choose a different lifestyle, i.e. one that is characterised by a decreased dependency on wage labour than is usually the case in Sweden.

For both cases dissemination is a true challenge. For the case of Finnängen the challenge consists of convincing people to choose investments in energy efficiency before spending their money on other things, such as cars, holidays or new kitchens. The approached used at Hälsingbo requires a lifestyle different from what is common today, and the dissemination challenge is likely to be far greater, as widespread lifestyle changes are harder to bring about than changes in consumption patterns. One could argue that the Finnängen approach is more likely to materialise under the current consumerist societal framework, given the right marketing strategy. However, voluntary simplicity was once a widespread sentiment in the U.S. after the 1973 oil crisis and as many as four to five million Americans were believed to live “whole-hearted” lives of voluntary
simplicity at that time, while almost half the population sympathised with the aim of voluntary simplicity [120]. The Hälsingbo approach may therefore be a good back-up strategy if things work out less well than the green growth and ecological modernisation advocates anticipate.

From a technical perspective it is interesting to see that low energy use does not necessarily require low U values. A combination of improved insulation in strategic places, temperature setbacks mainly during nights and a decrease in heated space area can yield a lower total energy use than is achieved with high technology in a large house with high indoor temperatures.

Somewhat surprisingly, both houses display rather significant sensitivity to user behaviour with regard to the temperature regime employed. It becomes clear from the simulations that Finnängen could achieve another 50% decrease in energy use if a different temperature regime was introduced, thus decreasing energy use by a whole 80% from the energy use before refurbishment. From a wider perspective, this suggests that the use of high technology coupled with temperature zoning, thermostat setbacks and a decrease of the heated area could be a powerful combination for reaching energy savings in the magnitude required to reach the long-term savings targets. Such an approach would also imply lower investment costs on the supply side, as neither the heat pump nor the solar panels would have to be dimensioned as large as they were in the case of Finnängen.

6.7 Conclusions

The two cases show that energy savings beyond 50% in existing detached houses are technically achievable in the very short term. The cases illustrate two extremes – one that is characterised by high capital intensity and use of advanced technology and one that is characterised by the opposite – low capital intensity and use of simple technology. A combination of the two approaches, i.e. combining temperature setbacks, zoning and decreased heated space area with the use of advanced technology could achieve even higher savings. The challenge with any of these approaches is not primarily of technical or economic character, but rather how such concepts can disseminate in the wider society in order to achieve the long-term savings targets. The following chapter will therefore explore the barriers to behavioural change and which strategies can be used to overcome these.
7. Barriers to Energy Efficiency and Strategies for Behavioural Change

7.1 Introduction

Many studies on energy efficiency potentials show that there is a huge potential that is economically feasible to realise (see for instance [34-36]). In reality, however, only little of this potential is being tapped. On the Swedish national level, as little as 15% of the economic potential for energy efficiency is believed to be realised [121]. This discrepancy is commonly termed the “Energy Efficiency Gap” [122] and numerous attempts have been made to explain the causes of the gap (cf. [121, 123, 124]). The prevailing explanation for the gap in literature is the existence of a number of barriers to energy efficiency. The term “barrier” stems in this context from neo-classical economic theory [124] and implies that different additional costs need to be added to the apparent cost of an energy efficiency measure. Sorrell et al. [124] offer a comprehensive overview of the different barriers and they admit that the economic models have their limitations. This is especially true in a household context and puts the findings from Chapter 5 in particular into a different light.

Two different concepts have tried to expand the limited economic barriers model. One is the concept of “bounded rationality”, which attempts to introduce insights from psychology into economic theory. In his model for bounded rationality Simon (in [125]) contrasts substantive and procedural rationality. Substantive rationality follows neo-classical economic theory and assumes that decisions are taken in accordance with formal optimisation models. Procedural rationality on the other hand acknowledges the greater complexity of human decision making and incorporates constraints on people’s attention, resources and ability to process information. Thus, decisions taken are more likely to be sufficiently satisfactory for the decision maker, rather than being economically optimal [124].

The other concept is completely detached from economic theory and has been termed “the human dimension” of energy use [46]. It has its roots in social psychology and behavioural sciences and has been used to a large extent to improve energy efficiency programmes. Sorrell et al. [124] criticise the concept for not being “framed in terms of discrete barriers” and that it is mainly based on empirical studies of household energy use. In the context of
this research project, both objections are of little relevance. Firstly, discrete barriers to energy efficiency as in economic theory with their focus on costs fail to recognise and describe the complexity of variables that are intrinsically tied to each other and which influence household level behaviour and decision making. The second objection is rather an advantage for understanding energy use in the detached houses this thesis focuses on. In the Human Dimension school, bounded rationality is dismissed as being a too weak concept since decisions often are not just “limitedly rational” but “systematically biased or erroneous” [126].

According to the Human Dimension school, energy use is in one way or another in all contexts governed by human behaviour. Stern [127] categorises energy use related behaviour as “environmentally significant behaviour”, although it needs to be noted that energy use is not only relevant from an environmental perspective. Stern [127] defines environmentally significant behaviour in two ways: Behaviour that actually has an impact on the environment (directly or indirectly) and behaviour that is “undertaken with the intention to change (normally, to benefit) the environment” but that does not necessarily have to have an impact on the environment.

Environmental behaviour can be of four different types according to Stern [127]: Environmental activism, non-activist behaviours in the public sphere, private-sphere environmentalism and behaviour in organisations. In the context of this thesis, private-sphere environmentalism is most relevant with regard to housing sector energy use. According to theory, environmentally significant behaviour is governed by four different causal factors: Attitudinal factors, which include norms, beliefs and values; contextual forces, which can be summarised as external constraints of social, political or physical character; personal capabilities for taking action, including education, skills, availability of money and time etc. and finally habit or routine, as behavioural change often requires breaking old habits and developing new ones.
If environmentally significant behaviour is to change, these contextual forces need to be addressed, especially regarding energy use on the household level. There exists quite some empirical evidence how this can be achieved, some of which is presented by Dietz et al. [128] in their work on the potential of household behavioural changes for reducing carbon emissions in the United States.

7.2 Explaining the Gap

Dietz et al. [128] use empirical evidence to show how successful behavioural intervention programmes have been. They use four different categories of behavioural changes related to building sector energy efficiency: Home weatherisation\(^\text{11}\) (W), change to more efficient equipment\(^\text{12}\) (E), equipment maintenance (M), equipment adjustments (A) and daily use behaviours (D). The most successful examples of weatherisation programmes used a combination of financial incentives and strong social marketing. They also had good quality assurance and possessed convenience features such as one-stop shopping, to further decrease barriers for household decision making (Table 27). Inducing change towards more efficient equipment required improved rating and labelling systems as well as additional information to households or retailers to be successful. It also required some financial

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\(^\text{11}\) This category includes measures such as improving attic or façade insulation, improving building air-tightness and installing energy efficient windows.

\(^\text{12}\) E.g. replacing inefficient heating, ventilation and air-conditioning (HVAC) equipment.
incentives for households or retailers and once again strong social marketing was a prerequisite. Successful interventions into maintenance and adjustment of equipment as well as daily use behaviours were characterised by use of mass-media messages coupled with household- and behaviour-specific information, as well as communication through individuals’ social networks. In these categories the exact combination of interventions varied very much with the targeted behaviour for each case.

**Table 27: Successful combinations of interventions for increased energy efficiency (from [128]).**

<table>
<thead>
<tr>
<th>Category</th>
<th>Most successful combination of interventions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weatherisation (W)</td>
<td>Financial incentives</td>
</tr>
<tr>
<td></td>
<td>Convenience features (e.g. one-stop shopping)</td>
</tr>
<tr>
<td></td>
<td>Quality assurance</td>
</tr>
<tr>
<td></td>
<td>Strong social marketing</td>
</tr>
<tr>
<td>Equipment change (E)</td>
<td>Improved rating/labelling systems</td>
</tr>
<tr>
<td></td>
<td>Other information for households and retailers</td>
</tr>
<tr>
<td></td>
<td>Financial incentives for households or retailers</td>
</tr>
<tr>
<td></td>
<td>Strong social marketing</td>
</tr>
<tr>
<td>Equipment maintenance (M)</td>
<td>Mass-media messages</td>
</tr>
<tr>
<td>Equipment Adjustments (A)</td>
<td>Household- and behaviour-specific information</td>
</tr>
<tr>
<td>Daily use behaviours (D)</td>
<td>Communication through individuals’ social networks</td>
</tr>
</tbody>
</table>

Dietz et al. [128] use these insights to estimate the “Reasonably Achievable Emissions Reductions” (RAER) that are available in the U.S. in a short-term perspective. In the context of this thesis, Reasonably Achievable Energy Savings (RAES) would be a more appropriate expression to use. Using RAES acknowledges that there is a large gap between theoretical techno-economic potential and real savings by factoring in **behavioural plasticity**, i.e. the “proportion of people who can be induced to act” in a certain time-perspective [129]. Behavioural plasticity can also be seen as a factor that summarises the complexity of all behavioural aspects of energy use into one figure. Thus, a more realistic estimate of potentials for energy efficiency improvements can be obtained from considering both techno-economic potential and behavioural plasticity. A high-impact action with a high RAES value would be one that has both a large techno-economic potential and a high behavioural plasticity. RAES (e.g. in kWh) can be calculated by multiplying the techno-economic potential \( Pot_{TE} \) (e.g. in kWh) with the behavioural plasticity \( Pl_B \) (in %):

\[
RAES = Pot_{TE} \times Pl_B
\]
where $P_l_B$ is estimated from empirical studies. Dietz et al. [128] provide estimates of $P_l_B$ for a number of energy efficiency measures that are available in the short term, under the assumption that the very best combination of interventions is used for promoting each measure. In their case $P_l_B$ is the percentage of people who have not yet adopted the energy efficiency measure but will do so by year 10. Table 28 below shows that changes in categories M, A and D are far more difficult to realise than in categories W and E.

Table 28: Estimates of behavioural plasticity for different behaviour changes in different categories according to [128], under the assumption that the most effective combination of interventions is used.

<table>
<thead>
<tr>
<th>Behaviour change</th>
<th>Category</th>
<th>Behavioural plasticity $P_l_B$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weatherisation</td>
<td>W</td>
<td>90</td>
</tr>
<tr>
<td>HVAC equipment</td>
<td>W</td>
<td>80</td>
</tr>
<tr>
<td>Low-flow showerheads</td>
<td>E</td>
<td>80</td>
</tr>
<tr>
<td>Efficient water heater</td>
<td>E</td>
<td>80</td>
</tr>
<tr>
<td>Appliances</td>
<td>E</td>
<td>80</td>
</tr>
<tr>
<td>Change HVAC air filters</td>
<td>M</td>
<td>30</td>
</tr>
<tr>
<td>Tune up AC</td>
<td>M</td>
<td>30</td>
</tr>
<tr>
<td>Laundry temperature</td>
<td>A</td>
<td>35</td>
</tr>
<tr>
<td>Water heater temperature</td>
<td>A</td>
<td>35</td>
</tr>
<tr>
<td>Standby electricity</td>
<td>D</td>
<td>35</td>
</tr>
<tr>
<td>Thermostat setbacks</td>
<td>D</td>
<td>35</td>
</tr>
<tr>
<td>Line drying</td>
<td>D</td>
<td>35</td>
</tr>
</tbody>
</table>

The figures presented in Table 28 provide a good explanation of the energy efficiency gap and show that not even the best designed intervention programmes have been able to eliminate the gap completely. It also shows that the thermostat setbacks suggested in Chapter 5 may not yield as high savings as the simulation results show, which is confirmed by Gupta et al. [101] who state that actually getting people to carry out and maintain thermostat setbacks is a great challenge. However, as already stated, the estimated implementation rate of profitable energy efficiency measures in Sweden is only 15% [121], which suggests that there is room for improvement of Swedish energy efficiency intervention strategies.

The evidence Dietz et al. [128] use to estimate the savings that could be achieved through household-level behavioural change has been used by other authors to develop guidelines for how to design successful intervention programmes. Two of these will be presented below.
7.3 Models for Behavioural Change

Stern et al. [129] present six principles that are required for successful interventions towards change of environmentally significant behaviour, based on experiences from empirical studies. (1) High-impact actions need to be prioritised and (2) they need to be provided with sufficient financial incentives. Some behaviour changes will require large up-front investments, others are already economically attractive and resources should be put into other types of interventions. (3) All interventions need to be marketed strongly, where marketing through individuals’ social networks has been shown to be quite successful, as it has higher credibility than mass-marketing programmes. (4) A crucial and difficult principle requires that valid information be provided from credible sources at the points of decision. An example would be that a retailer of solar heaters would have to be able to provide the right information and be seen as trustworthy at the very point in time when the household is making the decision to purchase the equipment. (5) Furthermore, the intervention needs to be kept simple, as “people economise on cognitive effort, not only money” as Stern et al. [129] put it. Large bureaucratic hinders such as extensive paperwork for applying for grants and correct, but irrelevant information are examples where simplification is needed. (6) Finally, quality assurance needs to be provided, to ensure people that they will actually get the benefits they expect. In the building sector, this could mean making it easy to find contractors that can be trusted on all accounts. In the context of this thesis, this could be solved for instance by certifying contractors to ensure that they have the right competence for deep renovation projects as is suggested by Heier [130].

While these principles appear reasonable, they are difficult to translate into concrete projects. A more comprehensive attempt to develop empirical evidence into strategic guidelines has been developed by McKenzie-Mohr [45] in his work on Community-Based Social Marketing (CBSM), a concept he describes as “an attractive alternative to information-intensive campaigns [as it] has been shown to be very effective at bringing about behavioral change”. Some proof for this claim is given by the fact that the CBSM web page lists 160 scientific publications that deal with residential energy efficiency from a CBSM perspective in one way or another, with the oldest articles dating back all the way to 1976 [131]. As the CBSM approach is self-proclaimed a pragmatic one [45], few of the studies presented on the web page follow the approach to the letter, but many of the elements that can lead to successful behavioural change can be recognised in the articles, most of which originate from the fields of behavioural science, consumer studies and different areas of psychology. A few recent studies in the field of waste management have followed the CBSM methodology more thoroughly and obtained tangible results with regard to sustained behavioural changes [132, 133].
The CBSM approach is based on five distinctive steps – (1) Selecting behaviours, (2) Identifying barriers and benefits, (3) Developing strategies, (4) Piloting and (5) Broad-scale implementation and evaluation. For each of these steps different tools are available that can be used to reaching the objective of bringing about behavioural change.

The reason why McKenzie-Mohr’s guidelines are discussed at length here, is that it represents the only comprehensive approach to changing environmental behaviour encountered in the literature review that is based on a broad scientific foundation. Although the CBSM approach is no exact manual for bringing about behavioural change, it provides inspiration for creating a well-informed and effective strategy for reducing energy use in the building sector, especially from a local or regional perspective.

7.4 Community-Based Social Marketing – An Overview

7.4.1 Selecting Behaviours

The first step is about determining which behaviours to target with an intervention programme. For the case of this study, energy use in detached houses has been identified as the key environmental behaviour that needs to be targeted. However, residential energy use is not a clearly defined behaviour, but can be further divided. The aim is to break down all energy use behaviours to a level where they are no longer divisible, in order to be able to identify the behaviours with the largest impact. Furthermore, behaviours should be “end-state”, i.e. residents should not only purchase energy saving light bulbs but also use them [45]. As already discussed, the actual impact of a behavioural intervention is determined by both its potential impact on energy use and the probability of the intervention materialising in reality, its behavioural plasticity. McKenzie-Mohr [45] adds another factor to the equation, penetration, i.e. the share of people who already have adopted the targeted behaviour. The lower the penetration rate, the more interesting it becomes to target the behaviour. Eq. 4 thus can be rewritten as:

\[
RAES = Pot_{TE}Pl_B(1 - Pen) \quad Eq. 5
\]

where \(Pen\) is the degree of penetration of an intervention. Taking into account the degree of penetration for different interventions can greatly alter the conclusions that can be drawn from lists such as the one presented in Table 28. If for instance more efficient heating systems already have reached a high degree of penetration (as for the case of heat pumps in Sweden, see
Chapter 2), then intervention programmes targeted at these will not have any substantial effect, despite the high behavioural plasticity for such measures. Thus, a good statistical foundation is required for selecting the right behaviours.

7.4.2 Identifying Barriers and Benefits
The second step of the CBSM approach involves identifying barriers and benefits with the overall aim to uncover all barriers (such as the ones presented in Figure 25) that will be addressed in the subsequent steps. McKenzie-Mohr [45] points out that “speculation regarding what leads individuals to engage in responsible environmental behavior should never be used as the basis for a community-based social marketing plan”, as the whole campaign may be misdirected if the wrong assumptions about barriers and benefits are made in the beginning. From contacts with decision makers from both public authorities and private companies in the context of this study, this point cannot be overstated. Speculation is resorted to all too frequently when proper background data are lacking. McKenzie-Mohr [45] suggest a four step approach to remedy this problem: (1) Review relevant articles and reports, (2) Carry out observations of people engaging in the behaviours that one wishes to promote or dissuade, (3) Conduct focus groups to explore the target audience’s attitudes towards these behaviours and (4) Enhance knowledge on barriers through a random sample survey of the target audience. In case of lack of time or money (as is often the case), steps three and four can be condensed into one step, with a simple survey on barriers and benefits experienced by the target audience.

7.4.3 Developing Strategies
The by far most work-intensive step of the CBSM approach is developing viable strategies to both encourage desired behaviours (by removing barriers and/or by increasing benefits) and to discourage undesired behaviours (by increasing barriers and/or by decreasing benefits). For best intervention effectiveness, McKenzie-Mohr [45] recommends to address both the behaviour that we intend to encourage and the one we want to discourage. The methods and tools that will be chosen in the end depends on which barriers and benefits were identified in the previous step and which behaviours were selected as relevant. McKenzie-Mohr [45] divides the pool of available methods and tools into seven categories

- Commitment
- Social norms
- Social Diffusion
- Prompts
- Communication
• Incentives
• Convenience

all of which will be briefly reviewed in the following sections. The different tools presented all address different types of barriers to engagement in sustainable behaviour, see Table 29 below. Note that the barriers should be interpreted as barriers for individuals to engage in non-divisible, end-state behaviours and therefore differ from the more comprehensive set of barriers, i.e. the causal factors presented in [127], which also include barriers on a higher hierarchical level.

*Table 29: Barriers and tools to address them (from [45]).*

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of motivation</td>
<td>Commitment</td>
</tr>
<tr>
<td></td>
<td>Norms</td>
</tr>
<tr>
<td></td>
<td>Incentives</td>
</tr>
<tr>
<td>Forget to Act</td>
<td>Prompts</td>
</tr>
<tr>
<td>Lack of Social Pressure</td>
<td>Norms</td>
</tr>
<tr>
<td>Lack of Knowledge</td>
<td>Communication</td>
</tr>
<tr>
<td></td>
<td>Social Diffusion</td>
</tr>
<tr>
<td>Structural Barriers</td>
<td>Convenience</td>
</tr>
</tbody>
</table>

**Commitment**

The intention with using commitment is to create action from good intentions. While good intentions do not necessarily lead to people taking action, McKenzie-Mohr [45] presents convincing evidence that even small commitments can lead to real action towards increased sustainability. Apparently, making small commitments, e.g. a commitment for supporting green electricity in general, alters people’s self-perception. When at later stages asked to actually subscribe to green electricity they feel pressure to act consistently with their previous commitment and are more likely to sign a subscription. Written commitments are more effective than verbal ones, and commitments that are made public are by far more effective than ones that are not. McKenzie-Mohr [45] recommends to ask for commitments at existing points of contacts (e.g. through contacts with electricity retailers) in order to increase cost-effectiveness and to decrease intervention into people’s lives. Furthermore, commitments should always be made voluntarily.

**Social norms**

According to the studies cited by McKenzie-Mohr [45], social norms can have a powerful influence upon sustainable behaviour. Norms can be of either injunctive or descriptive type. Injunctive norms tell us what behaviours are approved or disapproved of. Descriptive norms tell us what
behaviours we normally engage in. An example from the realm of household energy use would be sending out letters to electricity consumers telling them whether they consume more or less electricity than the average customer. However, studies cited by McKenzie-Mohr [45] have shown that customers who consumed less than average were likely to increase their electricity consumption. In such cases the descriptive norm can be enhanced with injunctive norms, such as praise for what they are doing and they are likely to continue to use less energy.

Social diffusion
Social diffusion is the process of how innovations, new ideas and behaviours spread in society. McKenzie-Mohr [45] and Stern [46] report that social diffusion occurs along the lines of social networks and that geographical proximity only matters if the behavioural change is visible to others. While the visibility of a behavioural change to others is of great importance, there are other factors that are highly predictive of social diffusion, too [45]:

- Does the new behaviour have a relative advantage over the behaviour it replaces?
- Is there a perceived risk with adopting the new behaviour, which could lead to financial loss or social disapproval?
- How challenging is the new behaviour with regard to its complexity?
- Is the new behaviour compatible with the norms and values of the target audience?
- Is it possible to trial the new behaviour before one needs to fully commit to it?

Concerning residential energy use, a complication is that many of the environmentally significant behaviours are invisible, which is why for example the installation of solar collectors is regarded more attractive than insulating the attic. This is one of the challenges that needs to be overcome in a successful intervention programme.

Prompts
The use of prompts, i.e. reminders, simply addresses the problem that people tend to forget to engage in sustainable behaviour, especially if it is of repetitive nature. As McKenzie-Mohr [45] states: “The purpose of a prompt is not to change attitudes or increase motivation, but simply to remind us to engage in an action that we are already predisposed to do” (emphasis added). In order to be effective, prompts need to be explicit, i.e. they need to target specific behaviours. Furthermore, they should be presented “as close in space and time as possible to the target behavior” [45]. One example for the use of prompts was the Swedish Nature Conservancy’s late 2008 send-out of stickers that were supposed to be attached to light switches, fridges, tumble dryers etc. with reminders to use these appliances in a more energy efficient way.
Communication
McKenzie-Mohr [45] defines communication as “effective persuasion” towards a more sustainable lifestyle. For the communication to be effective persuasion, many different requirements need to be fulfilled. To catch the attention of the audience, the message needs to be “vivid, concrete and personalized” [45]. Making the message personalised requires good knowledge of the target audience. Furthermore, messages are more effective if they indicate what an individual is likely to lose, rather than indicating potential gains. Thus, messages such as “if you replace your fridge with a new A++ rated one you can save 100 euro per year” are less effective than messages stating that “if you do not change your fridge to a new A++ rated one, you will be losing 100 euro each year”.

However, threatening messages are only effective if they also are accompanied by suggestions on how individuals directly can engage to reduce the threat. Otherwise risks are high that people simply will shut out the information. Once people start to engage in the new behaviour, it is advisable to provide feedback on the impact of their behavioural change, in order to increase chances that the change will become permanent. In general, communications become more effective when they are delivered in person (e.g. along the lines of social networks) and from credible sources. The message should also be clear, simple to understand and easy to remember (which in turn increases chances that the message will be discussed among people).

Incentives
Incentives are regarded a tricky issue with respect to CBSM, which is especially interesting with regard to the long-standing Swedish tradition of using grants and the like as an instrument for promoting energy efficiency (see Chapter 2). Abrahamse et al. [134] found that financial rewards for household energy saving efforts had immediate effects, but that they were rather short-lived. Therefore McKenzie-Mohr [45] suggests six guidelines with respect to the use of incentives:

1. The size of the incentive should be appropriate. It must be large enough to be taken seriously, but not larger than that.
2. The incentive and behaviour should be closely coupled and the incentive should be made available at the point of decision.
3. The incentive should be made visible to the target group.
4. Preferably, incentives should be used to promote desired behaviour, since punishing an unwanted behaviour not necessarily implies a greater engagement in the desired behaviour.
5. Removal of incentives needs to be considered carefully.
6. Disincentives foster creativity among people how to circumvent the disincentive.

Convenience
The final issue to consider regarding strategy, is to make sure that the behavioural change is convenient to engage in. McKenzie-Mohr [45] presents no general recipe on this topic, as convenience is very case dependent. For the residential energy context, he mentions that many low-cost devices, such as the installation of programmable thermostats, are inconvenient to implement. A door-to-door service could provide and install the devices in order to increase convenience.

7.4.4 Piloting
The pilot project is the final test of the CBSM strategy before it is implemented on a larger scale. McKenzie-Mohr [45] recommends to use a control group to ensure that the changes can really be accredited to the CBSM strategy. He also recommends actual measurements of the changes in target behaviours instead of self-reporting or similar approaches. Piloting is an iterative process with the intention of revising the approach until it is effective on the larger scale.

7.4.5 Broad-scale Implementation and Evaluation
Once a successful pilot has been conducted, the intervention strategy can be implemented on a broader scale. Continuous monitoring of the short- and long-term effects of the programme is recommended. It is also advisable to establish baseline data prior to the broad-scale implementation on the degree of penetration of the behaviours to be targeted.

7.4.6 Criticism
Elizabeth Shove put forward harsh critique against all behaviour-centred approaches to change towards increased sustainability [135]. She reduces all such approaches to the common label of ABC models, where A stands for attitude, B for behaviour and C for choice, suggesting that these models all assume that attitudes drive behaviour that people then can choose to engage in. This appears over-simplified, especially with regard to how for instance Stern et al. [136] elaborate on the subtleties of their environmental Value-Belief-Norm theory or the large amount of evidence used by McKenzie-Mohr [45] in the development of his CBSM approach.

Shove’s main critique, however, is that these models “marginalise and ... exclude serious engagement with other possible analyses” and that they “obscure the extent to which governments sustain unsustainable economic
institutions and ways of life”. This is likely to be true, but Shove states herself that “policy, as currently constructed, is necessarily incapable of conceptualising transformation in the fabric of daily life on the scale and at the rate required”. Shove draws the conclusion from this that more resources should be put into “the development of alternative ... models of social change and policy” and that researchers should “recognise that the policy arena is not of a piece”.

The conclusion I draw from this is an altogether different one, a conclusion I share with writers such as Rob Hopkins, the author for the Transition Handbook [137] and Bill McKibben, the author of Eaarth – Making life on a tough new planet [138]. Change will be small-scale, it must come from the grassroots level and it must be community based. This means that government and other large institutions, the ones Shove wants to put more responsibility on, cannot be counted on in the energy transition work, at least for the time being. As Hopkins [137] puts it, “Governments generally don’t lead, they respond [and] many of the decisions they will inevitably have to make as part of preparing for Powerdown [the energy transition] are perceived to be pretty much inconceivable from an electoral perspective”.

A concrete suggestion for how to remedy the situation that Shove sees as problematic, i.e. the ABC model as a paradigm, is barely discernible in her commentary, and frankly, time is not on our side when it comes to solving the great challenges we are facing – climate change and the energy crisis. Instead we should be pragmatic – even as academics – and use the knowledge we already possess to bring about the change needed for a smooth energy descent.

7.5 Outlook: Applying CBSM in Dalarna

Much of the work that was carried out in the context of this thesis lies well in line with CBSM methodology and could be used as a basis for a full-scale CBSM project. The selection of behaviours could be made using the statistics from Chapter 4 and some of the findings from Chapters 5 and 6, although further knowledge is needed in order to be able to identify true end-state behaviours. The identification of barriers and benefits could also be informed by findings from the latter two chapters. Furthermore, an on-going interview study, which will briefly be presented in this chapter, could prove valuable for obtaining a better understanding of individual house owners’ perspective on energy use. Although McKenzie-Mohr [45] suggests the use of focus groups to identify barriers and benefits, semi-structured interviews with home owners should have the same value. The first interviews in the study were done already in autumn 2011. The interviews were limited to owner-residents of single-family houses, with the exception of one case, where the author suspected almost unlimited agency of the interviewee over
his house. Geographically, the interviews have been limited to the rural parts of the municipality of Hedemora in the south of Dalarna county. Interviewees were selected through the author’s personal contacts, and people they recommended. The interviews took between 45 minutes and two hours.

The interviews were semi-structured and followed an interview guide, which was only marginally modified during the course of the study. About one third of the interview guide covered background questions regarding age, number of years the interviewee had lived in the house, number of residents in the house and so forth, as well as a few questions regarding the interviewee’s knowledge of current energy use for heating and household electricity. The remainder of the interview guide questions revolved around whether the interviewees had conducted any energy-related refurbishments, what they would like to do and what they feel they need help with. A few concluding questions regarded who should be responsible for energy efficiency in buildings in general and what the main obstacles could be for people to get engaged more into energy refurbishments. All interviews were recorded and then transcribed into text. Since the content of what was said mattered most, a transcription level close to level III [139], was chosen, i.e. pauses, overlaps and intonations were not transcribed, while most of the words used were maintained.

Preliminary findings from the first eight interviews show that energy use is one among many issues of relevance in households. However, most home owners had very little knowledge about which options were available to them to decrease energy use. Some believed that they already had done everything that was possible and most expressed strong distrust towards both authorities and potential contractors. The latter were generally regarded as biased. Few interviewees were aware of their heating costs and economic aspects were generally not regarded as a driving force for investing into energy efficiency, nor were environmental concerns regarded strongly. Aspects of personal comfort were stronger drivers with most people interviewed. The question of who should bear the responsibility to realise the energy savings objectives, all interviewed persons believed the individual home owners to bear the main responsibility. No further economic support from the state was demanded, however, people desired better communication from the authorities. Several of the interviewees requested better knowledge transfer from experts to home owners and between home owners.

The preliminary findings from the interview study provide some insights into designing a CBSM strategy that is tailor-made to the prerequisites of rural Dalarna. Apparently knowledge exchange and easier access to expert knowledge are two of the needs among home owners. Creating local study circles to increase commitment, and address the lack of knowledge could be one type of pilot study. Study circles could also speed up the process of social diffusion. Participation in study circles could be coupled to a
commitment to decrease energy use by a certain percentage during the course of the study circle. Incentives from for instance utilities, who have a strong interest in decreasing peak loads [130], could increase commitment further.

7.6 Discussion and Conclusions

The research presented in this chapter adds another layer of complexity to dealing with energy use in the building sector. The oversimplifying claims made in many of the much-quoted policy documents on the potential for energy savings in the sector show that there is a great knowledge gap even among professionals, and not the least among decision makers in the sector. Human behaviour is a complex affair and economic models do not suffice to capture the whole width of this complexity.

Looking back at the regulations and intervention programmes that were discussed in Chapter 2, it can be noted that there is much room for improvement towards more holistic and systematic intervention programmes. Swedish interventions for increased energy efficiency appear to be characterised by some randomness and a lack of systematic evaluations of the effects of different interventions. The insights from the Human Dimension school of energy use do not seem to be well understood with regard to the design of the intervention alternatives. This has implications for actions taken at the local and regional level, as improvements of the steering instruments are unlikely to occur in the short-term, as the recently published Proposal for a National Refurbishment Strategy for Improved Energy Efficiency in Buildings [11] illustrates. The proposal finds that new steering instruments should only be deployed in the case of true market failures. New information campaigns are the major steering instruments proposed and include the establishment of an information centre for energy efficient refurbishment, improved energy counselling as well as information directly targeted at banks. The proposal even explicitly excludes the analysis of steering means that could increase the rate of refurbishment in the building stock, and measures to encourage more far-reaching refurbishments are deemed to only have marginal effect on energy use in 2050. Thus, there is room for regional actors to find more effective ways forward with regard to energy efficiency.

Using CBSM could be one pathway to pursue and the findings of this licentiate thesis provide valuable input into designing a CBSM programme on the regional or even local level.
8. Discussion and the Way Forward

The different themes explored in this thesis show that the answer to the simple question of how a 50% decrease in energy use in buildings can be achieved is far from straightforward. At the core of the challenge lies the fact that the objective cannot be achieved without addressing existing detached houses, where more energy is used than in any other part of the building stock. This fact entails a number of further complications.

Current legislation is – despite some improvement efforts – not adequate for the challenge as there appear to be too many exemptions from the requirement on energy use reductions in major refurbishments, and no effective control mechanisms exist. Other steering instruments in use, such as energy performance certificates and the use of energy counsellors, are by other researchers not regarded as being effective means of achieving the objective. In the short-term, the legislative instruments will therefore have to be complemented by other instruments.

The second complication regards the very structure of the housing stock. The stock of detached houses is far more fragmented, heterogeneous and simply more small-scale than for instance the multi-family housing stock, which also has received the most policy attention. This makes finding generic refurbishment solutions more difficult, although there exists quite some potential for the measures analysed in Chapter 5, namely temperature management, attic insulation and window refurbishment or replacement. Furthermore, each refurbishment project will yield less savings than the refurbishment of a multi-dwelling buildings would yield and the total number of projects (and project owners) will be much greater. But even when assuming that the fragmentation and scale of the sector could be addressed properly, efforts in each refurbishment would have to far exceed the savings proposed in Chapter 5. This is necessary both to compensate for the houses in which savings around 50% cannot be achieved for technical, economic or cultural reasons and to compensate for rebound effects that are likely to occur.

The case studies presented in Chapter 6 show that such savings are quite achievable even in a short time frame, although they require either access to capital or the willingness to change lifestyle and to compromise on comfort to a certain extent. However, the greatest complication of all remains: How can the owners of the more than 1.8 million detached houses in Sweden and over 100,000 in Dalarna be convinced of to give priority to energy
refurbishments in their homes, with the aim of achieving savings well beyond 50%?

The research reviewed in Chapter 7 shows that the task will not be easy. Not only are the current steering instruments dismissed as being inadequate for the task at hand, but there is strong empirical evidence, too, that not even the most well designed intervention programmes will ever realise the entire techno-economic potential.

Thus, if the 50% reduction target is to be achieved, a sophisticated intervention strategy is required, a strategy that takes into account the many complexities brought to light in the course of the work on this licentiate thesis. With these complexities at hand – what would be a viable way forward to saving energy in buildings?

There are different routes that can be imagined, and in the study area of Dalarna a few important first steps have already been taken. For one thing there is a clear target of a 50% decrease in energy use in buildings until 2050, which is formulated in absolute terms and which, importantly, includes household electricity use. Furthermore, existing detached houses are recognised as key to reaching the energy savings objective and a pilot project on energy refurbishment in a number of sample houses was initiated in 2013 by a number of building sector actors from the county [140]. However, what is still missing is a clear vision of what type of society can achieve the savings aimed for. How can we work towards the target if we do not have a common vision? Are we dreaming of a high-tech society following the Finnången approach or is a future of voluntary simplicity more desirable? Or should we even demolish old houses at a faster pace and start again from scratch? Or is the vision one of a diverse society where all approaches are allowed? These questions need to be asked, and a vision needs to be developed, as much higher levels of commitment can be achieved if people know what they strive for.

Future studies methodology could prove to be a valuable tool to create a common vision for the work in the next four decades. In particular backcasting could be used as a method [141]. The first step in that method is to extrapolate current trends and match them with a long-term objective to see whether there is any discrepancy. As we saw in Chapter 4, there is a large mismatch between current trends and the long-term savings objective. The next step in the backcasting approach therefore aims at describing a preferable future [142] completely detached from the past and the present, where the long-term objective is fulfilled. From that desired future, potential pathways are traced back to the present situation.

However, one must ask who is to carry out such a backcasting exercise? With the degree of fragmentation in the building stock, it is impossible to make all voices heard, but at the same time the vision cannot be developed solely from a top-down perspective. Interviews with different building sector actors and stakeholders, such as the ones already conducted with home
owners in rural Dalarna, could in this respect provide some valuable insights to the vision building process. Questions that could be addressed in the backcasting exercise include: How do we envision people to live? Will people live in new or old houses? How many people will live in each house? Will urbanisation increase further or is the reverse possible? What will the climate be like and what does this imply for energy use? Who will be the principal actors when it comes to building energy use in 2050?

The vision work could be complemented with CBSM methodology and continued interviews as well as focus group exercises with home owners and building sector decision makers would be a reasonable next step. For the case of the home owners, such a study could give more insights as to what role energy plays in people’s everyday lives, which barriers they see to saving energy, but also which opportunities energy savings could open for them. For decision makers this could imply identifying their driving forces for or against energy savings in buildings and in which way they could contribute to realising the long-term savings targets. Subsequently, the findings from such a study could be used to design an intervention strategy, using the tools presented in Chapter 7.4.3 and a pilot project which specifically addresses home owners’ energy use behaviour. The pilot project could be conducted by the County Administrative Board or the energy counsellors in the region. Energy supply companies could prove to be valuable partners in this respects, although they will not have the obligation to help their customers save energy as is the case in other countries (see [143], Chapter 8 for why no energy efficiency certificates will be introduced in Sweden). Additionally, study circles with home owners with the objective to create commitment to conduct energy savings measures, could form part of a pilot study. The study circles could be hosted by action researchers and progress be evaluated scientifically.

To summarise, defining a clear vision for the housing stock in 2050, combined with a clear and sophisticated strategy for how to realise the first steps toward the vision, coupled with a first pilot study would form a firm basis for constructive and target-oriented work towards substantially lower energy use in the building sector. Scaling-up the results from the pilot study and potentially revising the strategy based on the findings from the pilot study would then be a natural continuation of the CBSM route. This work should be accompanied by qualified research that would evaluate both progress and the process employed in the campaign.
9. Conclusions

The challenges and complexities with regard to reducing energy use in buildings were analysed from a broad, interdisciplinary perspective. An understanding of the current state of the building sector was established by reviewing applicable legislation and by creating a detailed statistical overview of the building stock in the county of Dalarna, which was used as a study area in the thesis. Simulations of a number of sample houses were performed in order to estimate the savings potential available if a number of simple measures were implemented. The simulation results were complemented with two case studies that illustrated how far reaching savings could be achieved in the existing building stock. A review of the rebound effect and behavioural aspects of energy use was performed to highlight the complexities involved beyond technology and economy. Finally, strategies to overcome barriers to energy efficiency were investigated and potentials ways forward were suggested. The main findings of this licentiate thesis are:

- Outside the metropolitan areas of Sweden, the housing stock is dominated by detached houses, which currently do not receive the attention from national policymakers they would require. In Dalarna detached houses account for roughly 75% energy use in the housing stock.
- Swedish programmes to influence energy savings in existing houses have been badly designed and ineffective compared to the potential achievable savings.
- Dealing with energy use in detached houses from a regional or local perspective is a way forward.
- The techno-economic potential for affordable, simple energy savings measures is in the range of 30% savings in existing detached houses from today’s energy use, but not sufficient for reaching the 50% savings target, especially if potential direct rebound effects and implementation barriers are taken into account.
- Savings exceeding 50% must be achieved wherever possible in order to compensate for those buildings where such savings cannot be realised. This can be achieved with a deep renovation approach, which, however, has the drawback of not being profitable from a pure economic point of view.
• Substantial savings can also be achieved with an approach that is neither conventional nor of deep renovation type using low-technology solutions and behavioural changes with the drawback that the approach is unlikely to be scaled up to a large extent in the near future.

• A combination of using advanced technology and adopting behavioural changes would yield the greatest savings.

• Total (primary) energy use should be a guiding principle instead of specific energy use per m², which is currently used in the building codes.

• Household electricity and domestic hot water will have an ever greater share of total energy use and should therefore be included in efforts towards greater energy efficiency.

• Future work with the savings objective will have to take into account behavioural aspects of energy use and Community-based Social Marketing could prove to be a valuable tool for achieving sustained savings in building energy use.

• Direct and indirect rebound effects from energy efficiency measures will have to be taken into account by decision makers.
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