Igor Sartori

Modelling energy demand in the Norwegian building stock

Issues related to case studies and scenario analysis

Thesis for the degree philosophiae doctor

Trondheim, July 2008

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by
Igor Sartori

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Foreword

If after nearly four years of PhD studies this thesis does finally see the light, a few people need to be given credit for. Here I want to thank those people who have contributed, either directly or indirectly, to the achievement of this goal. I guess that I owe the first thank to the institution of NTNU itself and the so called Transes project, for having financed this PhD programme, hence having given me this great opportunity.

More personally, I want to thank Anne Grete for her unparalleled guidance during the entire period of my PhD work: from that very first telephone call one September morning four years ago until the last grammar check of this dissertation. She has always been encouraging and supportive, but also demanding at the due time; she always had a good word (and some good ideas) in the difficult moments. Her professional and human support has been the best supervision I could have ever asked for. I also want to thank Anne Grete for having been positive about my working abroad and from home; I have appreciated very much these opportunities and this flexibility. My thanks go also to Bjørn, with whom I have worked in closer touch; hectic work at times. I still remember that whiteboard full of sketches, diagrams and stuff; that full that at the end we had to take a picture of it, in order to be able to bring those ideas back home and work on them. I thank Håvard for the valuable collaboration and the long hours spent discussing algorithms, models, formulas and graphs. My thanks go overseas to Betsy, for the never ending days yelling at software that would do anything but what we wanted; but also for her sympathy. As she thought me to say, it has been “more fun than a barrel of monkeys”. Thanks also to Anne Sigrid and Claudia for many small daily things shared while sharing the office.

Not only professionally I have grown during these four years. I have to say that the time spent in Trondheim, and a bit around the world, has been mostly enjoyable and full of enriching experiences. I have learnt to appreciate and to understand (a bit, I hope) a country and a culture that are somewhat very different from my own – not to mention the language! I have had the chance to meet people from many countries and many cultures, and I have learnt a lot from them too. With them I have made a lot of experiences, went to plenty of hyttatur, played “una notte a Palermo” or “Carcassonne”, had dinners, chats, laughs, more dinners and cooking, went climbing, skiing, travelling, exchanged thoughts, ideas, points of view, feelings. A few parties also made their part. With some of them I have made friends, and I hope I have been able to give them as much as they have given to me. All the moments shared together are now part of what I am, and there are no thanks that can make up for what this means to me.

To Raffaele, Sara, Markus, Giuseppe, Marc and Lino: the enlarged (and improbable) “Italian family”. And again to Käthe, David, Glen, Nadina, Laila, Josep and Pascal. Thank you guys. Thanks also to Giulio, Miguel, Chiara and Barbara for the wonderful time in Boston. A special thought goes to Sofia, who chased me from the long cortado coffees in the warm afternoons of Barcelona to the too short skiing weekends in the snowy lands of Norway. And to Amalia for the intense time and the long skype conversations we had together. A myriad of other names and faces bounces in my head, connected to many situations and emotions that, even though they do not find space in these few rows, are well alive in me.

A most felt thanks go to my bonds in Italy. To the friends I am still friend with despite the distance I owe much. To my family. I am not quite sure about the idea they may have of what I am doing up here. I guess that while I used to be "one that works with computers", I have now turned into "one that researches with renewable energies". Anyway, I have always felt their love and their moral support for what I did, and I owe them the biggest thanks for instilling in me the constantly renewable energy that is indispensable for walking along the paths of life.

I would like to conclude this long round of thanks giving with a poetry that I find particularly suitable. It is one of those with a title; the title is *Pair of glasses.*

Pair of glasses

In life there are points of no return;
you taught me to look at the world
in another way.
I will never, anymore,
be able to see it as before.

Anonymous Greek

Trondheim, 19th of August 2008
Igor

Summary

Energy demand in the building stock in Norway represents about 40% of the final energy consumption, of which 22% goes to the residential sector and 18% to the service sector. In Norway there is a strong dependency on electricity for heating purposes, with electricity covering about 80% of the energy demand in buildings. The building sector can play an important role in the achievement of a more sustainable energy system. The work performed in the articles presented in this thesis investigates various aspects related to the energy demand in the building sector, both in singular cases and in the stock as a whole. The work performed in the first part of this thesis on development and survey of case studies provided background knowledge that was then used in the second part, on modelling the entire stock.

In the first part, a literature survey of case studies showed that, in a life cycle perspective, the energy used in the operating phase of buildings is the single most important factor. Design of low-energy buildings is then beneficial and should be pursued, even though it implies a somewhat higher embodied energy.

A case study was performed on a school building. First, a methodology using a Monte Carlo method in the calibration process was explored. Then, the calibrated model of the school was used to investigate measures for the achievement of high energy efficiency standard through renovation work.

In the second part, a model was developed to study the energy demand in a scenario analysis. The results showed the robustness of policies that included conservation measures against the conflicting effects of the other policies. Adopting conservation measures on a large scale showed the potential to reduce both electricity and total energy demand from present day levels while the building stock keeps growing. The results also highlighted the inertia to change of the building stock, due to low activity levels compared to the stock size. It also became clear that a deeper understanding of the stock dynamics was needed as a precondition for addressing energy demand in a more consistent way.

A methodology was developed for assessing in a coherent way both the stock and the building activities, i.e. construction, renovation and demolition. This methodology applies only to the residential stock. The analysis showed that in the coming decades renovation is likely to overtake construction as the major activity in the Norwegian residential stock.

Finally, the two models, the energy model and the activity model, were merged to perform an integrated analysis of the energy demand at a regional level. The result showed how considering the stock dynamics have a great impact in determining the effectiveness of a policy.

Table of Contents

1 Introduction

This thesis work is organised as a collection of articles. Each article is presented in a chapter, where it appears unabridged; only text formatting and layout may differ from the published version of the article. The chapters are grouped in two parts: Part I focuses on case study issues, while Part II focuses on scenario analysis issues. The content of each chapter and the way the articles are connected is briefly described later.

1.1 Background

Energy demand in the building stock in Norway represents about 40% of the final energy consumption, of which 22% goes to the residential sector and 18% to the service sector, as shown in Figure 1.1. The service sector comprises offices, shops, schools, hospitals and in general all buildings not devoted to residential use (industrial and agricultural buildings excluded). Similar figures are reported for the EU countries (DGET, 2004) and are also valid for western countries in general. One anomaly of the energy system in Norway is given by the fact that electricity production is more than 99% based on hydropower. The strong hydropower development of the last half century has guaranteed abundant and cheap electricity to the country; electricity has also been accompanied by the image of being environmentally friendly because it is based on a renewable source. These aspects have had a strong influence in shaping the energy demand in Norwegian dwellings (Bøeng, 2005) and in all buildings in general (Enova, 2006). There is a strong dependency on electricity for heating purposes, with electricity covering about 80% of the energy demand in buildings.

However, while the demand for electricity continues to grow both in the industrial and the building sector, the further potential for large scale hydropower development is limited due to protection of the remaining natural waterfalls. As a consequence national electricity consumption has increased more than the national power production, and unlike before Norway has actually been a net importer of electricity in the Scandinavian NordPool market six of the ten years from 1996-2005 (NVE 2008). This fact has economic consequences because the imported electricity is more expensive than that produced domestically, and at the same time the missed export represents a missed income. Electricity scarcity also poses environmental concerns because imported electricity comes from a production mix with higher CO_2 emissions (in the NordPool market marginal production is carbon intensive) and because new gas fired power plants are being planned in order to increase domestic capacity. Also in consideration of the CO_2 emission reduction target set by the Kyoto protocol, there is a strong interest in the opportunities to reduce electricity dependency as well as energy consumption in general.

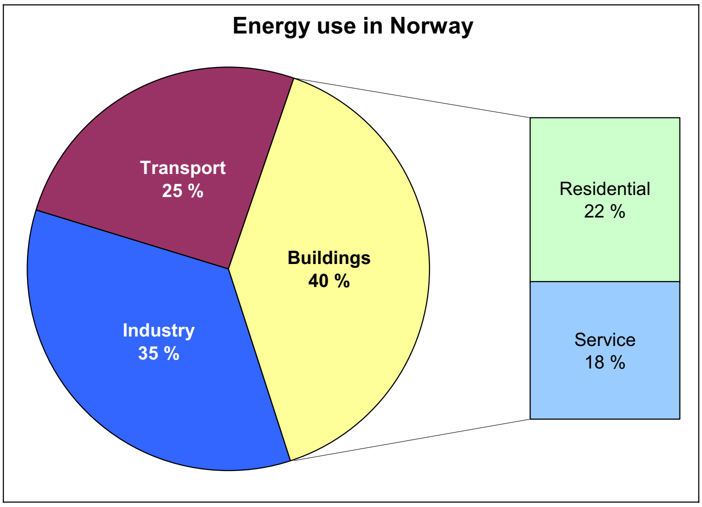

Figure 1.1 Final energy use in Norway in 2002, by sector.

The underlying rationale in this thesis work is that from an environmental and social economics point of view it is especially interesting to investigate measures that can limit the growth in electricity and energy demand in the building sector, and eventually reduce the overall consumption compared to present day levels. The building sector can play an important role in the achievement of a more sustainable energy system. The work performed in the articles presented in this thesis investigates various aspects related to the energy demand in the building sector, both in singular cases and in the stock as a whole. The purpose is to gain a bit deeper understanding of certain phenomena that lie behind the apparently ever increasing energy demand, and provide valuable insights that may help addressing the question of how to reduce it.

Two concepts will often recur throughout the articles: the European directive on the energy performance of buildings, and the passive house standard.

Like the countries that are member of the European Union, also Norway is on the process of adopting the Energy Performance of Buildings Directive (EPBD). This directive shall fully enter into force by 2009 (EPBD, 2002 and following standards). The EPBD prescribes that an energy certificate expressing the energy performance of the building shall be made available to the prospective buyer or tenant when buildings are constructed, sold or rented out. The energy performance is expressed by an energy class (the same way as it already happens for some electric appliances). The energy classes are labelled with letters from A to G, where A means most efficient and G means least efficient. Every country is responsible for the definition of its specific methodology for calculating the energy performance. However, a common requirement is that the methodology is based on both the evaluation of present stock average performance, named stock reference R_s, and the prescription performance for new and largely renovated buildings, named regulation reference R_r. The values of R_s and R_r are central to the definition of the energy classes. The proposed methodology and reference values for Norway are described in Pettersen et al. (2005) for the residential sector and in Wigenstad et al. (2005) for the service sector. The Norwegian scale, illustrated in Figure 1.2, is modified with respect to the European scale (EN 15217, 2007). In the Norwegian scale the class E is supposed to represent the average for the existing stock, while class C is the regulation requirement for new buildings.

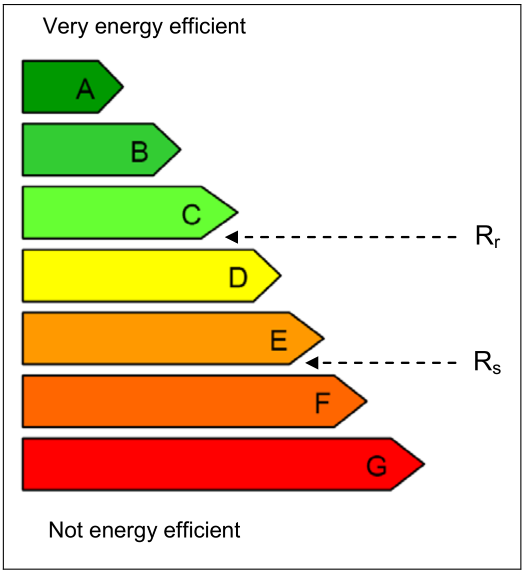

Figure 1.2 **Energy classes and reference values. R_r = reference for new construction, R_s = reference for existing stock.**

It is worth noting that this is the first regulation, at least in Norway, explicitly targeting the energy performance of buildings. Previous codes focused on technical prescriptions for the building components, such as the thermal properties of walls or windows, but did not specify the overall results to be achieved. Therefore, the EPBD classification of buildings based on their energy performance provides a suitable framework for the work in this thesis. Additionally, even though not defined in the EPBD, an extra energy class, named A+, will be used. The class A+ is meant to represent buildings that meet standards that go beyond the class A, as for example the “passive house” standard developed in Germany.

It is worth clarifying what is the difference between the term passive design, and the specific passive house standard. Passive design is a general term that refers to the design of buildings that provide a high level of comfort with minimised use of energy for heating, cooling, ventilation and lighting. This ability has been ‘rediscovered’ in recent times, after the architecture of the 20th century has been shaped by an era of cheap fossil fuels. In the past century a number of ‘active’ (mechanical) devices were developed to provide heating, cooling, ventilation and lighting to the interior of buildings. Such devices require energy for their functioning, and this energy has long been abundantly available and cheap enough for the building designers not to care much about it. As a result the indoor climate design focus shifted from the building envelope to the mechanical systems, and architects abdicated responsibility for environmental control to the engineers. Only in recent times has there been an increased awareness in the public arena that high consumption of energy resources is both causing significant environmental burdens, i.e. global warming, and rapidly depleting non-renewable resources. As a consequence, the era of cheap and abundant energy is close to an end. Because the building sector is responsible for a large part of the energy demand, at least in the developed countries, this has led to a rediscovery of the principles of indoor climate control through: manipulation of the building form, positioning of openings, control of solar gains, thermal performance of materials and their dynamic thermal behaviour, natural ventilation and so on; the so called ‘passive’ design. Hence, passive design is the general practice of seeking to maximise indoor comfort while minimising the intervention of active systems.

The passive house concept, on the other hand, is a well defined and codified standard. Much of the early work on passive design started in the US and in Europe as a consequence of the oil crises of the 1970s, and has continued until today receiving increasing attention. It is in this context that the concept of a passive house was developed in Germany toward the end of the 1980s. In 1991 the first passive house was built in Darmstadt, Germany; subsequently the *Passivhaus Institut* was founded in 1996. Since then there has been a proliferation of research activities, publications and conferences related to passive houses, and an ever increasing number of buildings with certification of compliance to the passive house standard is being constructed. Up to today more than 8.000 houses that conform to the current passive house standard have been built in Germany and elsewhere in central Europe (Ford et al., 2007), and this (still) niche market seems to be growing exponentially.

The success of this concept can be attributed to two factors. First, the clarity of its definition allowed the establishment of a certification scheme, thus creating the conditions for the building industry to develop certified products, for the public authorities to set up targeted policies and incentives, and for the end users to have a form of warranty on the quality of their investment and the secure achievement of the expected performance. Second, the achievement of a passive houses standard requires limited extra capital cost; compared with equivalent conventional constructions, projects realized in several European countries demonstrated an average extra cost lower than 10% (Feist et al., 2001). In the German climate, and more in general in the European continental climate, a passive house can guarantee good comfort conditions (defined in terms of indoor temperature and indoor air quality) without traditional heating systems and without active cooling. Required characteristics to achieve this result are very good insulation levels, including reduced thermal bridges and well-insulating windows, good air tightness, optimal use of solar passive gains, and a ventilation system with highly efficient heat recovery. Due to these improvements in the energy efficiency it is finally possible to simplify the heating system. The design heat load is small enough that it can be transported through the ventilation system by the air that needs to be supplied for air quality reasons. The whole heat distribution system can then be reduced to a small heating coil placed in the ventilation air supply unit. However, space heating does not necessarily have to be conveyed by the ventilation system. In all cases, though, the heating system will be greatly simplified and undersized compared to what is needed in conventional buildings.

The definition of the passive house standard, as elaborated by the Passivhaus Institut, involves specifications on parameters like the U-value of walls, roof and ground floor (in general < 0.15 W/m^{2}K), U-value and solar heat-gain coefficient of windows (≤ 0.8 W/m^{2}K and $\geq 50\%$ respectively) and air-tightness (index $n_{50} \leq 0.6$ ach). It also includes a number of recommendations on: use of fresh air pre-heating through underground ducts, ventilation rates (~0.3-0.4 ach), efficient heat recovery systems ($\geq 80\%$), limitation of the maximum heat load (≤ 10 W/m^2), the use of heat pumps, the use of solar thermal collectors for hot water, and the use of efficient electric lighting and appliances. Nevertheless, the passive house standard is hinged upon two major requirements:

- Net energy demand for heating ≤ 15 kWh/m^{2}y
- Primary energy demand for all purposes ≤ 120 kWh/m^{2}y

calculated on the net habitable floor area.

There has been, and there still is, a considerable interest in the European Union to expand the definition of the passive house standard and adapt it to different climates. Proposals for adaptation to the Nordic climate (approximately for latitudes above 60°) have been elaborated in the framework of the “Promotion of European Passive houses” project (PEP, 2007). Similarly, a proposal for the adaptation of the standard to the Mediterranean climate (approximately for latitude below 40°) has been elaborated in the “Passive-On” project (Passive-On, 2007). Unfortunately, such proposals have not yet led to an agreed and recognized standardization. It seems that the major requirement on primary energy is likely to remain valid also for these variants of the standard, while the requirement on heating (and cooling) demand may be climate adjusted (Andersen et al. 2008). However, in the rest of this work the term passive house will be used referring to the original German definition of the standard.

Figure 1.3 shows the energy consumption for a typical Norwegian detached house in different energy classes. The figures that define the classes E, C and A have been taken from the proposal for the Norwegian implementation of the EPBD and from the new building code (Pettersen et al., 2005 and TEK, 2007). The passive house, or class A+, is defined using the heating demand of a passive house (15 kWh/m^{2}y) while all other uses of energy are defined as in the class A. It can be seen that all energy figures refer to net energy, except for the class E data that is expressed in terms of delivered energy. This, in general, would not allow a direct comparison of class E with the other classes. A thorough and rigorous analysis of both net energy and delivered energy is developed in chapter 5. Nevertheless, as much as 70% of Norwegian dwellings are equipped for direct use of electricity for heating (Statistics Norway, 2001). Where heating is provided by direct use of electricity, delivered energy can be assumed equal to net energy. Then, the heating demand of a passive house (≤ 15 kWh/m^{2}y) is one tenth of the heating demand of an average house in the stock, and the total energy demand is about one fourth.

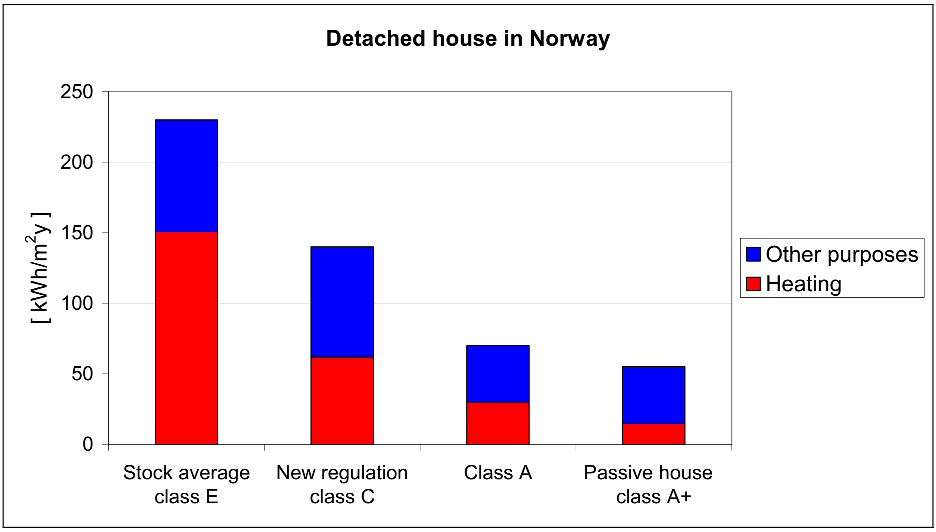

Figure 1.3 **Energy demand in typical detached house in Norway, according to different classes of energy performance.**

A detached house is any residential building other than a block of apartments (see chapter 5 for a more precise definition). Detached houses represent more than 80% of Norwegian dwellings, and are the single most important category in the entire stock, including residential and non-residential units, representing 57% of the entire building stock (see chapter 5). These numbers, together with the data in Figure 1.3, already give an idea of the large potential for reducing energy demand that is inherent in the design of energy efficient buildings, in both new construction and renovation works.

The passive house standard has been developed for dwelling units, both detached houses and block of flats. Nevertheless, an extension of the standard to non-residential buildings is also possible. An increasing number of examples of non-residential buildings that comply with the performance requirements specified by the passive house standard have been presented in the most recent editions of the Passive House Conferences (see for example ICPH 2006 and 2007). Nowadays, the PassivHaus Institut certifies also office buildings, schools, nursery houses, hospitals, sport halls and in principle any building that can satisfy the requirements on heating demand and total primary energy demand listed above. The main differences from a dwelling unit are given by the intensity and the time-distribution of the internal gains and the different paths of occupation, due to different activities performed in the building. The final requirements on the energy performance are unaltered, however. There is an increasing body of research on the subject. For instance, based on a collection of realised examples and case studies, in a recent publication the Passivhaus Institut has codified the recommendations and guidelines for the realisation of passive schools (Passivhaus-Schulen, 2006).

A remark should be made that in this thesis the terms "energy production" and "energy consumption" are sometimes used. It is obvious that energy intended in its physical meaning is a quantity that cannot be neither produced nor consumed. However, when energy is intended as a commodity, the terms production and consumption become appropriate.

1.2 The structure of the thesis

1.2.1 PART I – case studies

Chapter 2: Energy use in the life cycle of conventional and low-energy buildings: A review article
Sartori, I. and Hestnes, A. G.
Published in *Energy and Buildings*, 39 (2007) 249-257.

In this article a literature survey on the use of energy in buildings' life cycle is performed, in both residential and non-residential units. The purpose is to study the relation between the embodied energy and the operating energy, and how this varies in conventional and low-energy buildings. The rationale is to evaluate the net benefit of low-energy buildings in a life cycle perspective.

Based on the outcomes of chapter 2, the rest of the thesis focuses on the use of energy during the operating phase of buildings.

The next two articles could be regarded together, as two parts of the same case study. The case study was chosen to be the retrofit of a school building. This choice arose from considerations on the available information about the energy performance of buildings. The information available on the residential sector is generally more abundant and reliable than it is on the service sector (also because the residential sector is more uniform). Besides, more research work has been done on new construction rather than on renovation. Therefore, the choice was made to study the potential for energy improvements in the renovation of a non-residential building, in order to provide a bit more information where it is needed the most.

Chapter 3: Calibration of multiple energy simulations: case study on a Norwegian school building
Sartori, I. and Ricker, E.
In the Proceedings of the conference *CISBAT 2007*, 4-5 September, EPFL, Lausanne, Switzerland.

In this article the problem of calibrating the simulated energy consumption of existing buildings with metered records is addressed. Dynamic software for building energy simulation is used to model the building. The article investigates the possibility of using a Monte Carlo method in the calibration process. This has the double purpose of improving the manual calibration process, and to generate a set of multiple calibrated solutions. The rationale is that multiple calibrated solutions will provide the basis for a robust evaluation of energy saving measures.

The calibrated model of the school served as a starting point for the work presented in the next article. Having a model that is able to accurately reproduce the measured energy demand provides the basis for assessing energy saving potentials with a certain degree of confidence.

In parallel, the proposed calibration method served as the basis for a thorough parametric analysis on office buildings performed by Ricker (2008).

Chapter 4: Case study on retrofit of a Norwegian school: possible to achieve the passive house standard?
Sartori, I. and Wachenfeldt, B. J.
In the Proceedings of the conference *Passivhus Norden 2008*, 2-3 April, Trondheim, Norway.

In this article a series of retrofit measures are simulated, with the purpose of achieving the energy efficiency defined by the passive house standard. The rationale is to gain a deeper understanding of the possibilities to improve the energy performance through renovation in a non-residential building.

The experience gained with the case studies investigated in PART I was useful in developing the content of PART II, which addresses the entire stock of buildings. A number of issues arise when scaling up the analysis from single cases to an entire stock. The case studies analysis provided valuable insights for making better informed assumptions when modelling the building stock and developing scenarios for studying the potential evolution of the energy demand.

1.2.2 PART II – scenario analysis

Chapter 5: Modelling energy demand in the Norwegian building stock: scenario analysis based on activity flows, energy class and user preference
Sartori, I., Wachenfeldt, B. J. and Hestnes, A.G.
Preliminarly accepted for publication in *Energy Policy*, June 2008.

In this article a methodology for modelling the energy demand in the Norwegian building sector is developed. The resulting model has a demand side perspective, and makes use of several archetypes in order to describe the composition of the stock. The purpose is to study the effect of three hypothetical policies, and combinations of them, aimed at reducing energy and electricity demand. The rationale is to explore what the maximum energy saving potential is, both in terms of policy effectiveness and of time needed for changes to happen.

From modelling energy demand it became clear, already at an early stage, that it is of utmost importance to use the best possible estimates on the building activities, i.e. on: construction, renovation and demolition. At the same time there seems to be a chronic lack of data on the renovation and demolition activities, especially in the service sector, and, more in general, a lack of knowledge on how a stock evolves due to its internal dynamics. In order to provide a sound basis for energy modelling, it is first necessary to improve the understanding of such dynamics. That is therefore the content of the next article. Nevertheless, to pursue such a goal, it was necessary to narrow the scope to the residential stock only.

Chapter 6: Toward modelling of construction, renovation and demolition activities: Norway's dwelling stock 1900-2100
Sartori, I., Bergsdal, H., Müller, D. B. and Brattebø, H.
Accepted for publication in *Building Research and Information*, May 2008.

In this article a method based on a dynamic material flow analysis is presented, and applied to the Norwegian dwelling stock. The inputs to the model are socio-economic indicators and technical parameters. Several scenarios are considered in order to test the model sensitivity to the input's uncertainties. The purpose is to gain insights into the possible evolution of the dwelling stock and related activities in the future. The rationale is that a deeper understanding of the dynamics driving these activities is a precondition for a more consistent way to address material and energy demands.

In the next article an attempt is made to merge the two models developed in chapters 5 and 6. The original article was written in Norwegian and is reported in Appendix A. Chapter 7 presents the same study, but focuses more on methodological aspects.

Chapter 7: Mid-Norway as a pilot region for promotion of passive houses: A study of the potential
Based on:
Wachenfeldt, B. J. and Sartori, I., Midt-Norge som pilotregion for passivhus satsing: Potensialstudie, in the Proceedings of the conference *Passivhus Norden 2008*, 2-3 April, Trondheim, Norway.

In this article a model to study the energy demand in the residential sector in the Mid-Norway region is presented. The region in question is of particular interest because it poses the biggest challenges of the moment for expanding the electricity grid and power production in the area. The purpose is to estimate the potential for energy and electricity savings in the residential sector. The rationale is that, in combination with measures in the service and industry sectors, the need to increase power production and grid capacity may be reduced or completely eliminated.

Finally, the conclusive chapter briefly summarizes the findings of each article. In addition, an overall view of the work is given, with suggestions for future work to be done in order to improve and expand the scope of the issues treated in this thesis.

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Energy use in the life cycle of conventional and low-energy buildings: a review article

Sartori, I. and Hestnes, A. G.

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2 Energy use in the life cycle of conventional and low-energy buildings: a review article

2.1 Abstract

A literature survey on buildings' life cycle energy use was performed, resulting in a total of 60 cases from 9 countries. The cases included both residential and non residential units. Despite climate and other background differences, the study revealed a linear relation between operating and total energy valid through all the cases. Case studies on buildings built according to different design criteria, and at parity of all other conditions, showed that design of low-energy buildings induces both a net benefit in total life cycle energy demand and an increase in the embodied energy. A solar house proved to be more energy efficient than an equivalent house built with commitment to use "green" materials. Also, the same solar house decreased life cycle energy demand by a factor of two with respect to an equivalent conventional version, when operating energy was expressed as end-use energy and the lifetime assumed to be 50 years. A passive house proved to be more energy efficient than an equivalent self-sufficient solar house. Also, the same passive house decreased life cycle energy demand by a factor of three – expected to rise to four in a new version – with respect to an equivalent conventional version, when operating energy was expressed as primary energy and the lifetime assumed to be 80 years.

2.2 Definitions

Conventional building, or simply *Conventional.* Refers to a building built according to the common practice of a specific country in a specific period.

Conversion factor. Multiplicative coefficient that converts values from end-use to primary energy. Conversion factors vary from energy carrier to energy carrier and from country to country.

Embodied energy. The sum of all the energy needed to manufacture a good. It may or may not include the feedstock energy. Generally expressed in term of primary energy.

End-use energy. Energy measured at the final use level.

Feedstock energy. Heat of combustion of raw material inputs, such as wood or plastics, to a system. Generally expressed as gross calorific value.

Initial embodied energy. The sum of the energy embodied in all the material used in the construction phase, including technical installations.

Low-energy building, or simply *Low-energy.* Refers to a building built according to special design criteria aimed at minimizing the building's operating energy.

Operating Energy. Energy used in buildings during their operational phase, as for: heating, cooling, ventilation, hot water, lighting and other electrical appliances. It might be expressed either in terms of end-use or primary energy.

Passive house. A type of low-energy building; design is oriented to make maximum exploitation of passive technologies (eventually adopting also some active solar technology).

Primary energy. Energy measured at the natural resource level. It is the energy used to produce the end-use energy, including extraction, transformation and distribution losses.

Recurring embodied energy. The sum of the energy embodied in the material used in the rehabilitation and maintenance phases.

Solar house. A type of low-energy building; design is oriented to make maximum exploitation of solar energy (with both passive and active technologies).

Total Embodied energy. The sum of both initial and recurring embodied energies.

Total energy. The sum of all the energy used by a building during its life cycle (total embodied energy plus operating energy multiplied by lifetime).

2.3 Introduction

Buildings demand energy in their life cycle, both directly and indirectly. Directly for their construction, operation (operating energy), rehabilitation and eventually demolition; indirectly through the production of the materials they are made of and the materials technical installations are made of (embodied energy). Case studies that explicitly consider the phases of construction, demolition and relative transportation of materials (see Table 2.2, col. Other Energy) all show that the sum of the energy needed for these phases either is negligible or settled at approximately 1% of the total life cycle energy need. In some of the literature however, energy for construction and relative transportation is included in the definition of the initial embodied energy, showing that there is no clear agreement on how this should be handled. Only a few studies include the phase of recycling building materials after demolition (see Table 2.2, col. Recycling). Although these studies offer an interesting point of view, the mass of literature does not consider waste management as part of a building's life cycle.

Therefore, this paper focuses only on operating energy and embodied energy in the life cycle of buildings. The recycling phase has not been taken into account. Until few decades ago it was known that operating energy represented by far the largest share in the life cycle's energy bill, ranging to about 90–95% even when accounting only for the heating demand [1] [2]. More recently, the increased awareness of environmental problems related to energy processes together with a trend of ever increasing energy demand from the building sector have lead building designers to develop more energy efficient design criteria, and states to implement building codes that are more and more stringent on energy requirements. In addition, increased interest and better methodologies, such as Life Cycle Assessment, LCA, provide better understanding and better estimation of energy (and other environmental) aspects in the life cycle of any sort of good. Hence, the relative importance of operating and embodied energy has changed.

The purpose of this article is to clarify the relative importance of operating and embodied energy in a building's life cycle, especially in low-energy buildings. Design of low-energy buildings directly addresses the target of reducing the operating energy. This is done by means of both passive and active technologies. Passive technologies include, for example, increased insulation, better performing windows, reduction of infiltration losses and heat recovery from ventilation air and/or waste water. Active technologies include, for example, heat pumps coupled with air or ground/water heat sources, solar thermal collectors, solar photovoltaic panels and biomass burners. There has been, and there is, a variety of approaches to designing low-energy building, and it is not in the scope of this paper to analyze their peculiarities. However, a common aspect is that a reduced demand for operating energy is achieved by increased use of materials, and especially of energy intensive materials, both in the building envelope and in the technical installations. It has even been argued for a substitution effect [3], for which the benefit of reducing operating energy is, to a large extent or completely, counterbalanced by similar increases in the embodied energy.

2.4 Method

For what it is relevant in this paper, Table 2.1 and Table 2.2 give a comprehensive overview of the main characteristics of cases presented in literature. Where a source is reported to have more than one case, it means that either more than one building or different versions of the same building were presented in the source itself. In some of the literature data were found in tables and/or text form, while in other only graphs were available (see Table 2.1, col. Data). In the latter case numerical values have been estimated from the graphs, thus they might be subject to slight imprecision.

Table 2.1 Overview of literature, general data.

Source	Country	Case numbers	Type of Building[a]	Area [m^2]	Lifetime	Data[b]
Adalberth et al., 2001 - [4][c]	Sweden	1-2	Res m	700 - 1,520	50	G
Adalberth, 1997 - [13]	Sweden	3-5	Res	129 - 138	50	T
Adalberth, 1999 - [9]	Sweden	6-13	Res m	700 - 1,520	50	T
Cole and Kernan, 1996 - [14]	Canada	14-25	Off	4,620	50	T
Fay et al., 2000 - [15]	Australia	26-27	Res	128	50	T
Feist, 1996 - [5]	Germany	28-33	Res	156	80	G, T
Hallquist, 1978 - [1][d]	Norway	-	Res m	?	40	T
Hannon et al., 1978 - [2]	USA	34-35	Res	457	annualized	T
Mithraratne and Vale, 2004 - [6]	New Zeland	36-38	Res	94	100	G, T
Scheuer et al., 2003 - [10]	USA	39	Oth	7,300	75	T
Suzuki and Oka, 1998 - [16]	Japan	40-49	Off	1,253 - 22,982	40	G
Thormark, 2002 - [7]	Sweden	50	Res	120 x 20	50	T
Treolar et al., 2000 - [11]	Australia	51	Res	123	30	T
Winther and Hestnes, 1999 - [3]	Norway	52-56	Res	110	50	G, T
Winther, 1998 - [12][e]	Norway	-	Res	110	50	T
Zimmermann et al., 2005 - [8]	Switzerland	57-60	Oth	national average	annualized	T

[a] Res: residential one- and two-dwellings, Res m: residential multi-dwellings, Off: office, Oth: other.

[b] G: graph, T: table and/or text.

[c] Two additional versions to Adalberth [13].

[d] Screened out because it presented the necessary data only in percentages.

[e] Additional data on initial embodied energy to Winther and Hestnes [3].

Cases differ for climate, country, type of building, type of construction, assumptions on indoor climate and source of data (whether measured or calculated). For this reason it would be inappropriate to directly compare the cases against each other. Rather, the authors' intention has been to assess the relative importance of operating and embodied energy within each single case, and then to compare these relations amongst the various cases. Cases also differ in size and estimated lifetime. In order to neutralize these differences, energy figures were normalized per unit of area and time [kWh/m^{2}y]. After a first screening, the authors decided to exclude from the analysis the case presented in [1] because it presented the necessary data only in percentages.

Another major difference is whether data were expressed in the form of primary or end-use energy. End-use energy is measured at final use level, and so it somehow expresses the performance of a building. Primary energy is measured at the natural resource level, including losses from the processes of extraction of the resources, their transformation and distribution, and so it expresses the real load on the environment caused by a building. In other words, the same hypothetical building placed in different countries but with similar climates is likely to have very similar figures about end-use energy. The difference in terms of primary energy, however, can be significant because of the different energy carriers available for thermal purposes (like district heating, natural gas, biomass or electricity only) and/or because of the different ways to produce electricity. For example, Norway: 98% hydropower [3]; Sweden: 49% nuclear and 44% hydropower [4]; OECD mix: 56% fossil fuels and 40% nuclear [4]. Information on energy carriers and relative conversion factors found in the literature was fragmented, so this aspect was not taken into consideration in this study. Therefore, all figures presented in this paper refer to undifferentiated, overall amounts of energy.

Concerning operating energy, some sources expressed it as primary, others as end-use, while few sources did not give clear specification (see Table 2.2, col. Operating Energy). The latter are shown with a question mark. The supposed form of energy assumed, as inferred by comparison with the known cases, is given in brackets. Concerning embodied energy, no clear statement about primary/end-use was found in any of the sources. It was here assumed that data were expressed as primary energy, as this is the common praxis in LCA analysis of products and related industrial activity and environmental impact. The analyzed cases were grouped in two categories, according to the expression of their operating energy, primary or end-use.

Table 2.2 Overview of literature, energy data.

Source	Operating Energy	Heating only	Embodied Energy	Recycling	Other Energy	LCA
Adalberth et al., 2001 - [4]	End-use		I, T +f	X	X	X
Adalberth, 1997 - [13]	Ens-use		I, T +f		X	
Adalberth, 1999 - [9]	End-use		I, T +f	X	X	
Cole and Kernan, 1996 - [14]	? (Primary)		I, T		X	
Fay et al., 2000 - [15]	Primary		I, T			
Feist, 1996 - [5]	Primary		I, T			
Hallquist, 1978 - [1]	? (End-use)	X	I		X	
Hannon et al., 1978 - [2]	? (End-use)	X	I		X	
Mithraratne and Vale, 2004 - [6]	Primary	X	I, T			
Scheuer et al., 2003 - [10]	Primary		I,T +f		X	X
Suzuki and Oka, 1998 - [16]	? (Primary)		I, T		X	
Thormark, 2002 - [7]	Primary		T +f	X		
Treolar et al., 2000 - [11]	Primary		I, T			
Winther and Hestnes, 1999 - [3]	End-use		T +f			
Winther, 1998 - [12]	End-use		I, T +f	X		
Zimmermann et al., 2005 - [8]	Primary		T			

I: initial, T: total, +f: feedstock energy included.

The total number of cases analyzed amounted to 60. The cases have been assigned a progressive number according to the alphabetical order of their source (see Table 2.1, col. Case numbers); and in the rest of the paper they are presented in the graphs by their number. Whenever relevant to the discussion, the source is also mentioned. As it is in the purpose of this article to stress the differences between conventional and low-energy buildings, this feature is always highlighted.

According to [5] a low-energy building can be defined as one having an annual requirement for heating below 70 kWh/m^{2}y, expressed in end-use energy. Yet, data reported in the same source (in graphic form) show that such a building has an overall end-use operating energy of about 120 kWh/m^{2}y; that can be converted into about 200 kWh/m^{2}y of primary energy requirement. Although conversion factors between end-use and primary energy depend on the energy carriers used and the energy system of a specific country, a common definition of low-energy building was necessary also for cases with primary energy figures. Generalizing the definition found in [5] to all the cases presented in this paper, and considering a little margin because of the possible imprecision in converting graphical data into numbers, the authors have adopted the following definition: a low-energy building is one having an operating energy $\leq$ 121 kWh/m^{2}y when expressed in end-use energy[1], or $\leq$ 202 kWh/m^{2}y when expressed in primary energy.

2.5 Results

The sum of both operating and embodied energy, which virtually amounts to the total life cycle energy (except for ca. 1% used for erection, demolition and transportation as mentioned above), was calculated and normalized in kWh/m^{2}y for each case. The results are shown in Figure 2.1 and Figure 2.2, where the cases have been sorted in ascending order of their normalized total energy. Case numbers followed by an exclamation point mark those cases where operating energy considered only heating.

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[1] $\leq$ 70 kWh/m^{2}y when heating only is considered.

Case #30, which had only embodied energy, is the "Self-sufficient solar house" presented in [5] and will be further discussed.

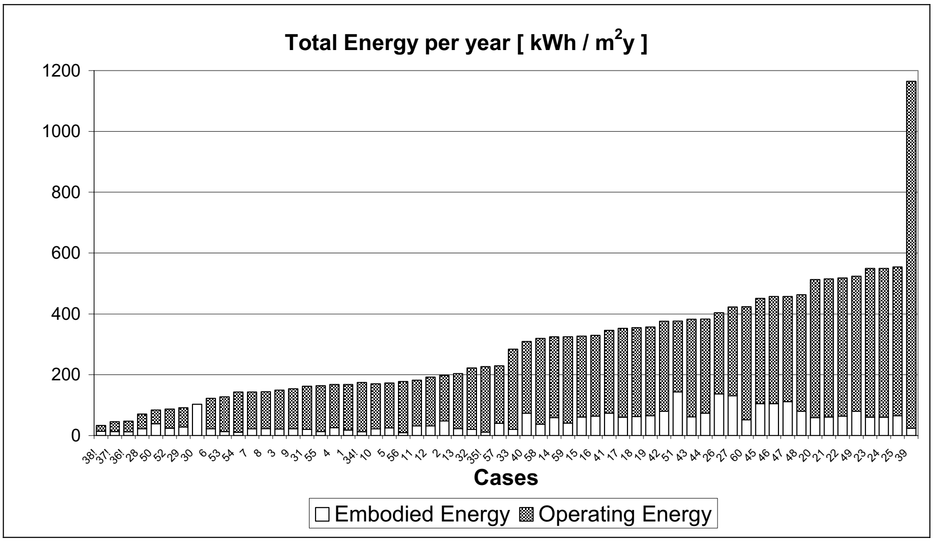

Figure 2.1 **Normalized total energy for the 60 cases.**

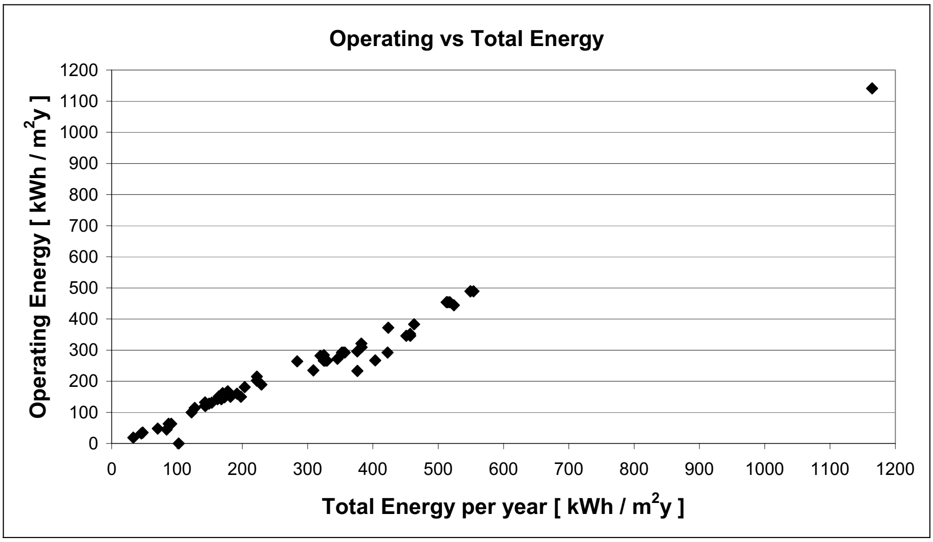

Figure 2.2 **Relation between operating and total energy for the 60 cases.**

Figure 2.1 shows that operating energy represented the dominant part in all the cases, while Figure 2.2 shows a linear relation between operating and total energy. In other words, despite all the differences between the individual cases, such as materials and construction techniques employed, size and type of building, climate and so on, the general trend turned out to be uniform. This is due to the dominant role of operating energy that trims down the influence of all other differences.

In order to assess possible differences between conventional and low-energy buildings, the results for primary and end-use energy were examined separately. Figure 2.3 and Figure 2.4 mirror the previous graphs for only those cases where operating energy was expressed as primary energy, while Figure 2.5 and Figure 2.6 refer to cases with end-use energy.

Low-energy building cases with data on primary energy were found in these sources: #28-32 in [5]; #36-38! (heating only) in [6]; #50 in [7]; #57 in [8]. The cases in [6] and [8] resulted in matching the definition of low-energy building adopted in this paper, although they were not presented as such in the original sources. Low-energy cases occupy the left-most positions in the graphs.

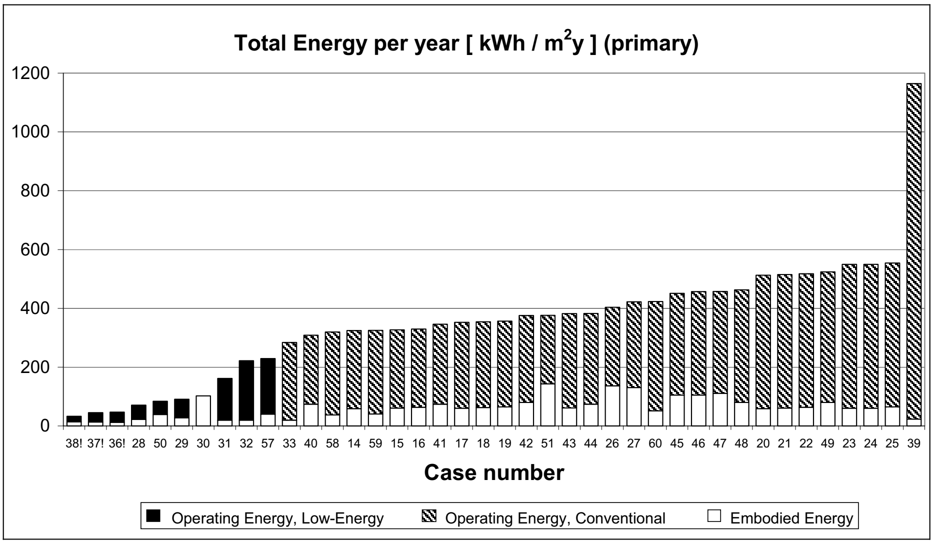

Figure 2.3 **Normalized total energy for primary energy cases.**

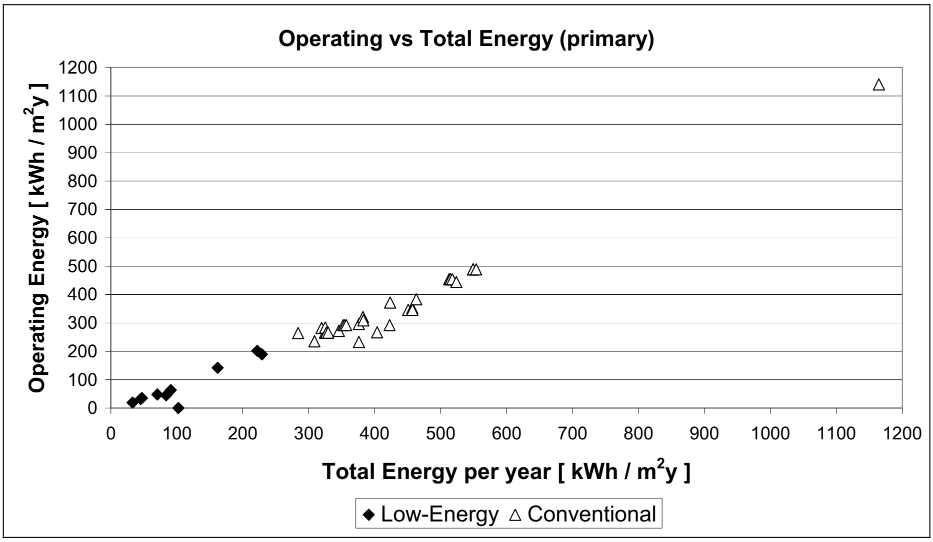

Figure 2.4 **Relation between operating and total energy for primary energy cases.**

Low-energy building cases with data on end-use energy were found in these sources: #6-8 in [9]; #52-53 in [3]. The cases in [9] resulted in matching the definition of low-energy building adopted in this paper, although they were not presented as such in the original sources. The graphs present just one singularity. Case #54 had a slightly lower total energy demand than cases #7-8 even though it had higher requirements for operating energy. It should firstly be noticed that differences in total energy among the three cases were very small. Secondly, they referred to different countries: cases #7-8 Sweden, case #54 Norway. This might explain the higher figures for embodied energy (expressed in primary energy terms) in #7-8.

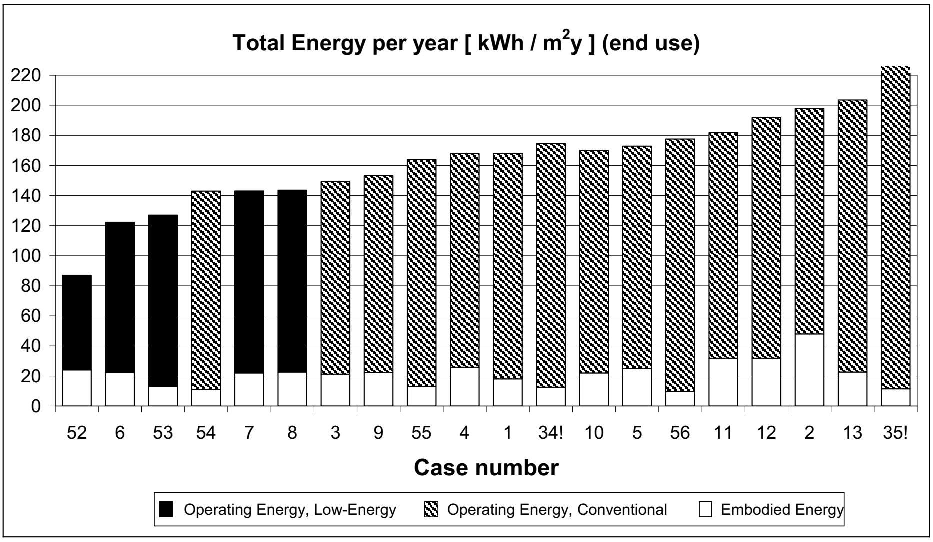

Figure 2.5 **Normalized total energy for end-use energy cases.**

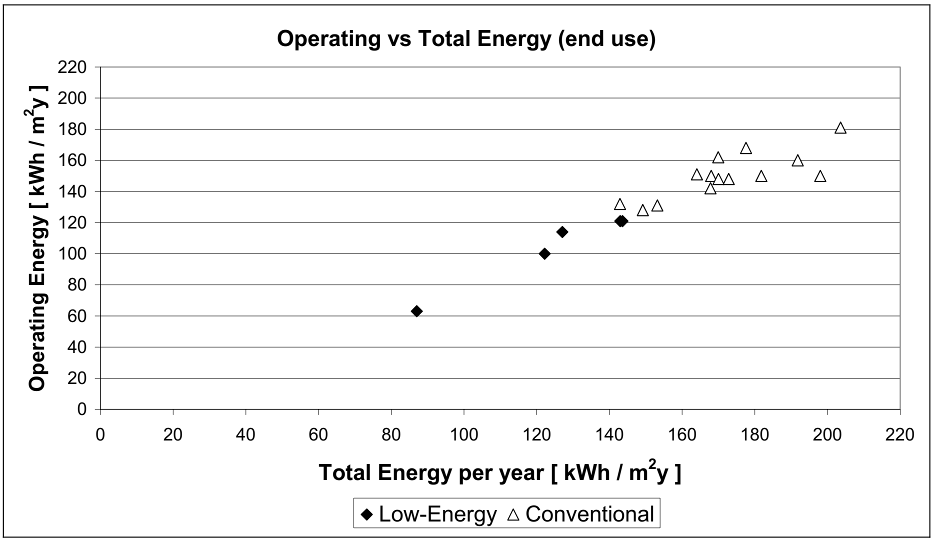

Figure 2.6 Relation between operating and total energy for end-use energy cases.

The results presented until here show that buildings with low energy requirement for their operation also result in being the best energy performing in absolute terms. Nevertheless, it might be argued that although a relation between operating and total energy needs exist, it is not a cause-effect relation. It might be argued that it is somewhat the indirect consequence of external variables, as for example the climate, that influence the demand for operating energy but does not affect the embodied energy. Thus, a favorable climate would produce the case of a building that requires little energy for operation, and consequently a low total energy regardless of the role of embodied energy and the building's design. Even though that seems not to be case here (considering that 7 of the 15 low-energy buildings were found in countries like Norway, Sweden and Switzerland; countries that can hardly be said to have favorable climates[2]), it is worth sharpening the investigation on this point. For those cases that matched the definition of low-energy the embodied energy's share of the total ranged between 9 – 46%. The minimum was found in [5] and the maximum in [7]. Conventional buildings had shares ranging between 2 – 38%, the minimum found in [10] and the maximum in [11]. These wide ranges are in good part related to the different backgrounds of each case. Estimation of embodied energy values can vary greatly from country to country, according to which energy carriers are predominantly available, the transformation processes that generated those carriers from the natural energy sources, and the efficiency of the industrial and economic systems that produced the materials. The differences from case to case are, indeed, simply too great to allow any further general conclusion.

In order to achieve a better understanding of the interplay between embodied and operating energy and its repercussions on the total energy needs, different versions of

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[2] The other cases were found in Germany and New Zealand.

the same building have to be analyzed at parity of all other conditions. Two studies were found in literature that coped with this aspect [3] and [5], and they are discussed here. [5] analyzed six versions of a residential unit in Germany and presented life cycle results in primary energy, while [3] analyzed five versions of a residential unit in Norway and presented life cycle results in end-use energy (see Figure 2.7 and Figure 2.8). Both studies analyzed both conventional and low-energy buildings. The conventional cases were named, in [5]: “Ordinance 1984”, and in [3]: “Code 1987”, “Code 1997” and “Green”. All the others were low-energy buildings. The percentages reported in the graphs refer to the embodied energy (initial plus recurring). It is worth reporting that the cases named: “Self-sufficient solar” and “Passive, as built” in one article, and “Solar IEA”, “Solar case2” and “Code 1997” in the other, respectively, referred to buildings actually built. The other cases referred to hypothetical versions of the same buildings.

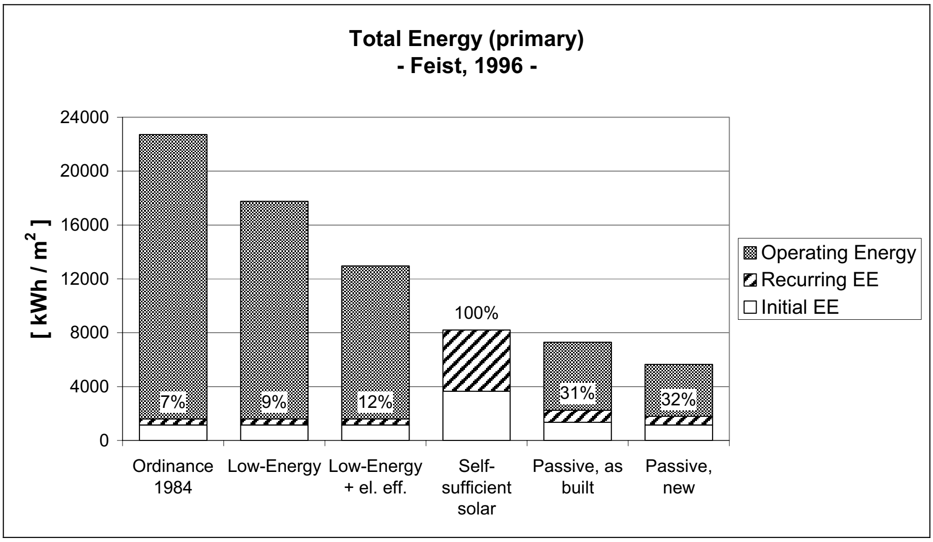

Figure 2.7 **Life cycle energy of the six versions in Feist [5]. “Ordinance 1984” is a conventional building, all the others are low-energy.**

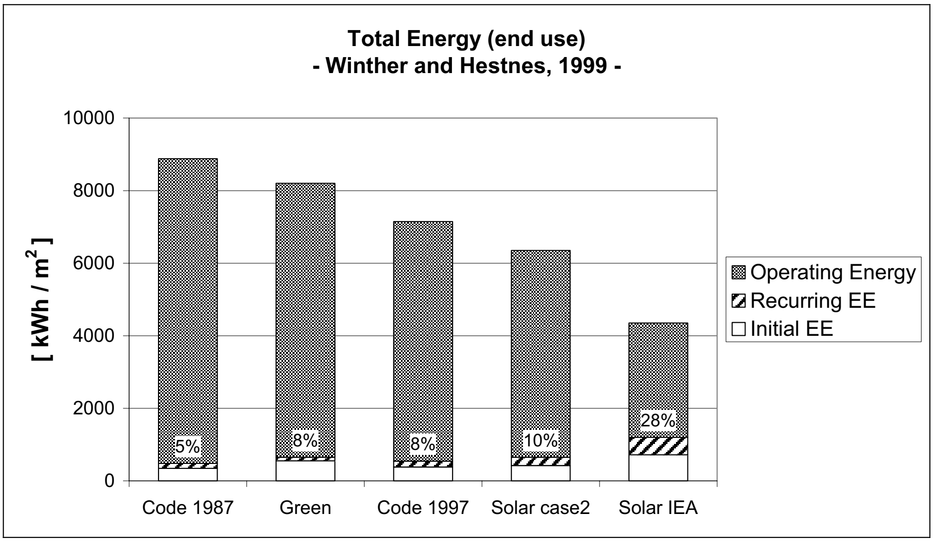

Figure 2.8 **Life cycle energy of the five versions in Winther and Hestnes [3]. "Solar case2" and "Solar IEA" are low-energy buildings, all the others are conventional.**

The results from the two studies show that low-energy buildings are not those buildings that just happen to demand little energy for whatever external cause. Low-energy buildings are the result of specific design criteria; and, at parity of all other conditions, they demand less operating energy and less total energy than if built according to conventional criteria.

Both studies showed that the amount of embodied energy used in any sort of low-energy version was higher than in the conventional ones, both in percentage and absolute. Both studies also showed that the trend of increasing embodied energy was accompanied by a trend of decreasing total energy, with the only exception being the "Self-sufficient solar" house in [5]. This house requires no energy delivery for its operation – neither fuels nor electricity – as all the energy it needs is locally produced (exploiting solar and wind sources) and stored. So, total and embodied energy are coincident. However, the high embodied energy needed to install and maintain all the additional technical equipment exceeded the requirements generated by the two versions representing the passive house standard.

The passive houses could achieve a great decrease in total energy use over the life cycle with just a little increase in the embodied energy. In the original source the author explained that the relatively small increase in embodied energy, in spite of using additional materials to make the house highly insulated and air-tight, is explainable by the fact that no conventional heating system was needed. The heating demand (very little after all the passive measures were applied) was met through the supply air. The reported initial embodied energy was 1,171 kWh/m^2 for the "ordinance 1984" version and 1,391 kWh/m^2 for the "passive, as built" version. In other words, with an increment in initial embodied energy of just 220 kWh/m^2 (about the equivalent of 1 year of operation for the "Ordinance 1984" house) the "Passive, as built" house could achieve a threefold decrease in the total energy, with an assumed lifetime of 80 years. The new version, "Passive, new", was expected to achieve a fourfold decrease (operating energy in primary energy terms).

In [3] the version named "Green" referred to a building designed with careful attention to the materials used. Here the use of synthetic materials was reduced to a minimum by substitution with natural, or "green", materials that could perform the same functions, while no special attention was devoted to minimize operating energy requirements. The results for the "Green" version were worse than those for low-energy buildings. The embodied energy was somewhat higher than in the conventional versions, and this is attributable, according to the original source, to the cellulose fiber used for insulation. The authors reported that cellulose fiber has higher energy intensity than conventional insulation materials, because its feedstock potential is lost when it is impregnated against fire. The "Solar IEA" house, when compared with the conventional cases, was shown to require about double the embodied energy while at the same time bringing about a factor two in net benefit over a life cycle of 50 years (operating energy in end-use terms).

Another way to look at the same cases is to project their energy demand on a temporal diagram. Figure 2.9 refers to [5] and Figure 2.10 to [3]. For simplicity, the recurring embodied energy was first annualized and then assumed to occur regularly on a yearly basis regardless of the actual maintenance periods. That is the reason why the lines presented in the graphs here do not show a stepwise behavior, as they do in [5].

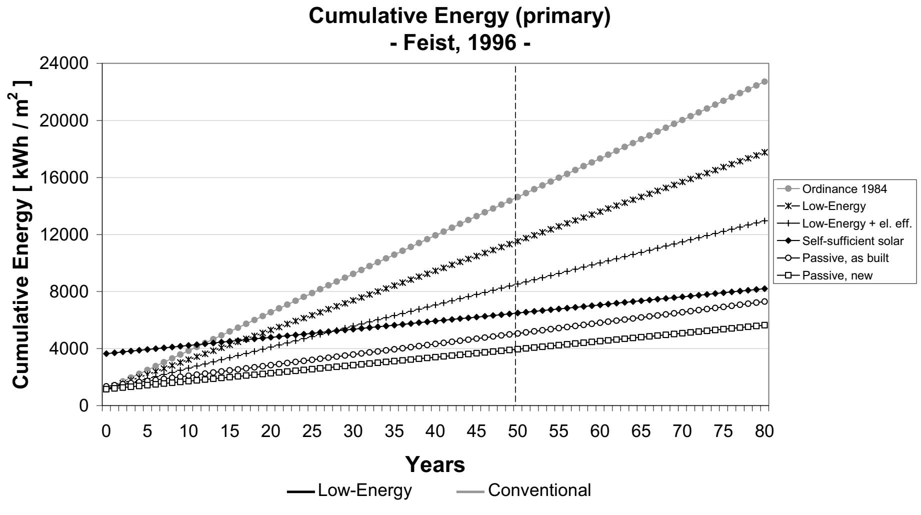

Figure 2.9 **Cumulative total energy in Feist [5]. "Ordinance 1984" is a conventional building, all the others are low-energy.**

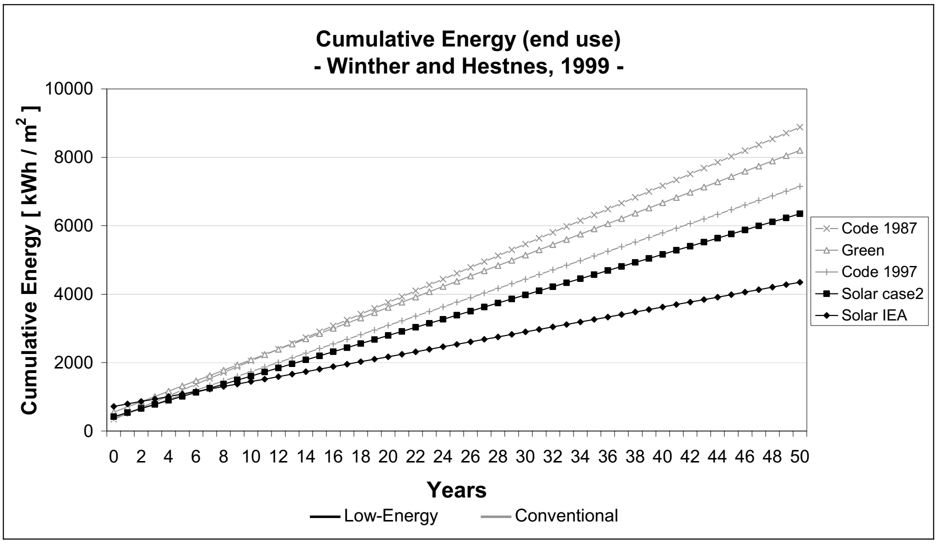

Figure 2.10 **Cumulative total energy in Winther and Hestnes [3]. "Solar case2" and "Solar IEA" are low-energy buildings, all the others are conventional.**

The graphs show how the higher initial embodied energy in low-energy buildings is largely paid back during the lifetime. It is worth noting that at no point in time is the energy of the "Self-sufficient solar" house lower than that of the passive house versions. Also, the divergence between the cases is more accentuated in Figure 2.9 (see values after 50 years – dashed vertical line) than in Figure 2.10. Of course the two graphs refer to different cases, but the higher divergence is also due to the fact that the energy was expressed in primary energy terms in Figure 2.9.

2.6 Conclusions

The analysis of 60 cases found in literature showed that operating energy represents by far the largest part of energy demand in a building during its life cycle. It has also been shown that there is a linear relation between operating and total energy, valid through all the cases despite climate and other contextual differences. Hence, low-energy buildings result in being more energy efficient than conventional ones, even though their embodied energy is somewhat higher. Differences in contexts could however not allow for assessments of general validity regarding embodied energy.

Analysis of case studies of buildings built according to different design criteria, and at parity of all other conditions, showed that design of low-energy buildings induce both a net benefit in total life cycle energy demand and an increase in embodied energy.

A solar house, a type of low-energy building, was shown to be more efficient than an equivalent building designed with careful attention to the use of "green" materials but with no special energy measures. The same solar house, when compared to an equivalent conventional building, required about the double of embodied energy while at the same time reduced the total energy need by a factor two, when operating energy was expressed as end-use energy and the lifetime assumed to be 50 years.

A passive house, another type of low-energy building, was shown to be even more efficient than an equivalent self-sufficient house. When compared with an equivalent conventional building instead, the passive house demanded only slightly more embodied energy while it reduced the total energy need by a factor of three, when operating energy was expressed as primary energy and the lifetime assumed to be 80 years. A new version of the passive house was expected to achieve an overall factor of four.

In conclusion, reducing the demand for operating energy appears to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle. Embodied energy should then be addressed in second instance. As regards to this subject, part of the literature surveyed suggests that there is a potential for reducing embodied energy requirements through recycling ([4] [9] [7] and [12]). Even though in this paper, as in the major part of literature, buildings' life cycle was defined from construction to demolition, to widen the boundaries of analysis in order to include the recycling phase would offer a means to include that potential. Finally, it is also possible to broaden the scope of analysis beyond pure energy accounting, in order to directly address a set of specific environmental loads caused by buildings and their operation. [4] and [10] have applied a full Life Cycle Assessment, LCA, analysis in their studies. They showed that buildings' life cycle phases had different effects on various impact categories; they also concluded that the demand for energy in the operating phase was the single most important factor.

2.7 References

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Calibration of multiple energy simulations: case study on a Norwegian school building

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3 Calibration of multiple energy simulations: case study on a Norwegian school building

3.1 Abstract

This work illustrates a methodology for generating a set of calibrated building energy simulations that match predefined criteria. The rationale is that multiple calibrated solutions will provide the basis for a more robust evaluation of energy saving measures than just one calibrated solution. A case study is performed on a 30 year old school building located in Trondheim, Norway. The total building energy consumption is recorded and is used to evaluate the accuracy of simulation results. The authors identify a set of 15 simulation input parameters that have both an influential effect and some level of uncertainty. These parameters are allowed to vary between a minimum and maximum value. A Monte Carlo method is used to generate random combinations of the allowed parameter values, resulting in multiple parameter vectors, on the order of hundreds or thousands. These vectors are then simulated, and the resulting energy consumption is evaluated against measured data. Those vectors that obtain the best fit are considered as candidate solutions. The final result is the identification of a set of top 20 candidate solutions.

3.2 Introduction

The use of computer simulations for estimating the energy performance of buildings is becoming more and more common in both design and retrofit projects, especially for the evaluation of energy saving measures. However, there is not a generally accepted procedure for accomplishing this. A preliminary literature search [1-4] shows that one typical practice is to manually calibrate a single building model; where calibration means the iterative adjustment of several parameters until the results of the simulation match well with measured utility data. Such a procedure is time intensive, requires a high level of user skill, and unavoidably turns out to be strongly biased by the personal judgement of the analyst. This is in addition to the fact that the problem itself is under-determined; meaning that due to the great number of interdependent variables and parameters, and the uncertainty associated with their estimation, there is an intrinsic inability to identify a unique solution. The acceptance of a single solution neglects these inherent uncertainties, and weakens the confidence with which energy savings can be predicted. In their recent work [5] Reddy et al. proposed a method that accounts for this uncertainty by finding multiple calibrated building energy models. The proposed procedure utilizes a Monte Carlo method to generate a solution space from which calibrated models can be identified. The work performed in this research builds upon the method proposed by Reddy et al. [5].

The building used in this case study is the Steindal elementary school, located in Trondheim, Norway (Latitude: 63° 36'; Longitude 10°, 23'). The Steindal School serves some 340 students and 40 administrators. The main building was built in 1978, with an additional wing, or annex, constructed in 1997; the total area is ca. 4800 m^2 divided between two floors, as indicated in Figure 3.1*a)*.

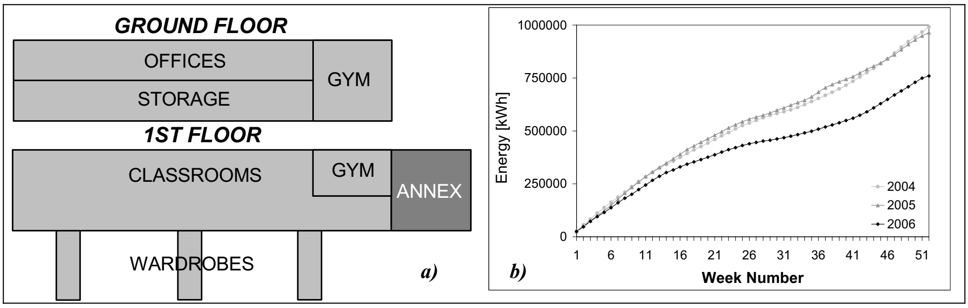

Figure 3.1 ***a)* Floor plan of the school; *b)* Energy consumption for 2004, 2005 and 2006.**

Outdoor air is supplied by two balanced ventilation systems with heat recovery, one in the main building and one in the annex, while heating is supplied locally in each room by electric resistance radiators; the building has no cooling system. Electricity is then the only energy carrier used by the school, and hourly data on consumption are available from the local electricity company from 2004 through 2006. The cumulative energy consumption, presented in Figure 3.1*b)*, indicates a significantly lower consumption in 2006. This is due partially to temperature differences between the three years, but is predominantly the result of changes in schedules of operation and temperature settings made by teachers and students of the school in the context of a communal programme aimed to teach and promote energy savings.

3.3 Method

A procedure adapted from that proposed by Reddy et al. [5] was followed in performing this work. The steps of this procedure are outlined in Figure 3.2, along with a brief description of their application to this case study. The focus has mainly been on the evaluation of the procedure for reaching calibrated solutions, while the estimation of energy saving measures is left to future work and is presented here only briefly with an example, for completeness.

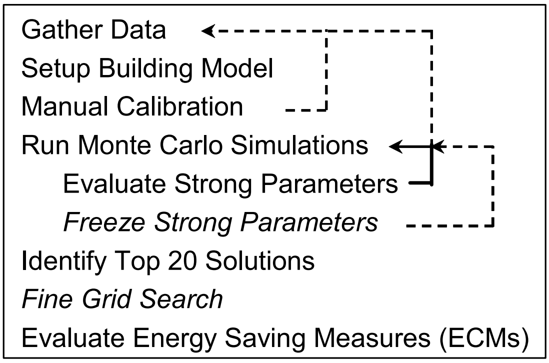

Figure 3.2 **Scheme of the procedure. Steps in italics or dashed lines are optional.**

Data was gathered from technical drawings, documentation, site visits to the school and meetings with building managers and architects. The Trondheim municipality provided real-time ventilation and temperature data from their remote control centre. Drawings and documentation were obtained from the school, and conversations with building managers and architects provided further information about the construction. The building was modelled using "EnergyPlus" as the simulation software [7].

The authors have developed two models of the building, here referred to as Detailed and Simple; the comparison of results from the Detailed and the Simple models will be a major focus. The Detailed model has 7 zones (six of them are visible and labelled in Figure 3.1*a)* while the seventh is the under-roof buffer space) that were chosen based on differing patterns of use. The Simple model has 2 zones (indicated by the lighter and darker grey areas) that were dictated by the presence of two separate ventilation systems. The basic year of simulation is 2006; for this year detailed information on operating schedules and temperature settings were collected from dialogue with the personnel both at the school and the municipality. This information was used in defining the Detailed model, which, due to the high quality of this data, was able to be calibrated on both a weekly and monthly time-scale. For this reason the Detailed model is used as a reference case. However, the weekly calibration of the Detailed model is time consuming, requires more detailed information on the building's materials and systems, and is often not an option simply because monthly utility bills are the only measurements available. The Simple 2 zone model employs more generalized schedules for the school and uses a monthly time-scale for calibration, making it more representative of a typical case in energy simulation. Further, the Simple model takes less time to simulate in EnergyPlus, roughly 25 seconds per simulation, while the Detailed model takes around 65 seconds on a typical PC. In order to test the robustness of the methodology the Simple model simulation was also run for 2005 and 2004. In the absence of adequate weather data for Trondheim, weather data for a typical meteorological year in Oslo were used, with the exception of outdoor temperature for which hourly values were available for Trondheim for all of the simulated years.

After the data collection was concluded a series of "best guess" values were available for each of the parameters. Starting from these values the authors performed a traditional manual calibration of the Detailed model – prior to Monte Carlo analysis – through a series of adjustments and refinements until the results on energy and power consumption had a good match (see equations (3.1(3.1), (3.2) and (3.3)) with measured data from the electricity company. Doing this allowed for the identification of 15 parameters whose effect on the results is significant and whose value, at the same time, is known with some degree of uncertainty. The list of these parameters is presented in Table 3.1 together with a brief description.

The next step of the procedure is the Monte Carlo analysis. As suggested in [5] a number between 10 and 20 parameters (15 in this case) are selected for being both influential and known with some level of uncertainty. These parameters are allowed to vary within a defined range, nominally selecting three possible values for each of them: low, middle and high, as shown in Table 3.1. For each parameter the value resulting from the manual calibration of the Detailed model was chosen as the middle value (or value 2); while the low and high values (or values 1 and 3 respectively) were defined in order to contain the original best guess for that parameter – see the last two columns of Table 3.1. In general, the deviations from the middle values were around ± 15%, and were used to define a coarse grid of parameter values.

Table 3.1 **List of the 15 parameters adopted in the Monte Carlo analysis. Values in brackets are used for the Simple model, but not for the Detailed. HVAC and SFP are abbreviations for Heating, Ventilation and Air Conditioning and Specific Fan Power, respectively.**

param.	**group**	**description**	**1 = low**	**2 = middle**	**3 = high**	**unit**	**manual calibration**	**original best guess**
p1	**Envelope**	Mineral wool conductivity	0.036	0.043	0.05	W/m-K	2	2
p2		U-value old windows	2.8	3.3	3.8	W/m^2-K	2	1
p3		U-value new windows	1.5	2	2.5	W/m^2-K	2	1
p4		Ground temperature	12-14	14-16	16-18	°C	2	3
p5		Infiltration	0.2	0.3	0.4	ach	2	2
p6	**HVAC**	Heating coil U-value	3500	3750	4000	W/m2-K	2	2
p7		Heat exchanger η, Main	40% (45%)	50% (60%)	60% (75%)	---	2	3
p8		Heat exchanger η, Annex	40% (45%)	50% (55%)	60% (65%)	---	2	3
p9		SFP, Main	1000 (1200)	1200 (1500)	1400 (1800)	W/m^3/s	2	1
p10		SFP, Annex	500 (600)	600 (700)	700 (800)	W/m^3/s	2	1
p11		Ventilation rate, Main	10	11	12	m^3/s	2	2
p12		Ventilation rate, Annex	1.8	1.9	2	m^3/s	2	2
p13	**Int. loads**	Internal Loads	100	120	140	kW	2	2
p14	**Settings**	Temperature setting	18 (19), -2	20 (21.5), -2	21 (23), -2	°C	2	1
p15		Schedule	low	middle	high	---	1	1

At this point, trying all the possible combinations would mean performing the unreasonable number of 3^{15} = 14,348,907 simulations. The Monte Carlo method, instead, generates random combinations of the allowed parameter values (1, 2 or 3), resulting in multiple parameter vectors, on the order of hundreds or thousands. These vectors are then passed to the simulation software, and the resulting energy consumption is evaluated against measured data.

The fit between simulation results and measured utility data is evaluated for both power and energy, and is quantified using the normalized mean bias error (NMBE) and the coefficient of variation of the root mean square error (CV). The criteria for selecting calibrated solutions are defined according to ASHRAE Guideline 14-2002 [6] that suggests a NMBE<5% and a CV<15%, as shown in equations (3.1) and (3.2), where: y_i = measured value, $\hat{y}_i$ = simulated value, $\bar{y}$ = average of measured values, and n = length of data series: 52 weeks or 12 months. When a parameter vector produces results that satisfy these criteria it is called a candidate.

$$NMBE = \frac{\sum_{n} y_i - \hat{y}_i}{n \times \bar{y}} \leq 5\% \quad \textbf{(3.1)}$$

$$CV = \sqrt{\frac{\sum_{n} (y_i - \hat{y}_i)^2}{n-1}} \times \frac{1}{\bar{y}} \leq 15\% \quad \textbf{(3.2)}$$

In order to rank the candidates a secondary criterion is used, called the goodness of fit (GOF), defined in equation (3.3). When the above criteria are satisfied for both average energy consumption (kWh) and peak power demand (kW), the resulting GOF is about 11%. Nevertheless, results from [5] suggest the conjecture that satisfactory accuracy in future prediction of energy saving measures is achieved by those candidates that have a GOF of about 6% (the lower the better).

$$GOF = \sqrt{\frac{NMBE_{kWh}{}^2 + NMBE_{kW}{}^2 + CV_{kWh}{}^2 + CV_{kW}{}^2}{4}} \cong 6\% \quad \textbf{(3.3)}$$

An important step in the procedure is the identification of strong parameters. The parameter strength is a measure of its effect on the results of the simulation; when a parameter is strong it will tend to appear amongst the candidates with a preferred value, or with a non-random distribution of values (1, 2 or 3). The strength of a parameter is quantified using the chi-square test, as suggested in [5]. The chi-squared test is a well-known statistical method to test the randomness of a distribution: the higher the value, the less random the distribution. When only three values are possible (degree of freedom = 2), as in our case, it can be said within a 99% interval of confidence that a parameter is strong, meaning not randomly distributed, when its chi-square value is above the threshold of 9.21. The formula for calculating the chi square is shown in equation (3.4), where: $p_{\exp}$ is the expected probability (number of candidates divided by three), and p_{obs} is the observed occurrence.

$$\chi^2 = \sum_{s=1}^{3} \frac{(p_{obs,s} - p_{\exp,s})^2}{p_{\exp,s}} \geq 9.21 \quad \textbf{(3.4)}$$

The strong parameters describe those areas where uncertainty in the inputs is most critical to the results of the calibration. This means that strong parameters are important in recognizing where further information needs to be gathered, or where a fine grid search could be performed. In order to identify the strong parameters iteratively higher numbers of simulations are run. Alternatively, the strong parameters are “frozen” at their most probable value and the Monte Carlo analysis is re-run on only the remaining parameters (thus searching in a reduced solution space) in order to identify new strong parameters.

Finally, the top 20 candidates, those with the lowest GOF value, are accepted for the evaluation of energy saving measures. Optionally, a fine grid search can be performed on these top 20 parameter vectors with the goal of further improving their GOF values. The fine grid search further subdivides in three sub-ranges the values for each of the strong parameters and simulations are run for all of the possible combinations for the top 20 solutions. The total number of simulations for the fine grid search amounts to 3^m, where m is the number of strong parameters.

3.4 Results and discussion

The Monte Carlo analysis began by running batches of simulations for the Detailed model. As the Detailed model had been manually calibrated the main purpose of running the Monte Carlo analysis was to test its validity as a tool for identifying further candidate solutions. Simulations were run starting with a batch of 250 vectors of random input combinations and continuing with 500, 1000, 2000, 4000 and 8000 trials. In [5] the authors suggest using the identification of strong parameters as a means to determine the convergence of the Monte Carlo analysis; this point proved to be controversial in the case study presented here. Some parameters were identified as strong in all of the batches, while others showed an “oscillating” strength, such that the same combination of strong parameters was never identified in successive batches. Despite this behaviour the algorithm seemed very stable with respect to the generation of candidates. Plotting on a scatter-chart the values of NMBE and CV, as in Figure 3.3*a)* and *b)*, it is apparent that the distribution of results intensifies with increasing simulations but does not change pattern. Similarly, the improvements in the GOF of the top 20 candidates did not show significant variation. The same behaviour was observed for the Simple model, see Figure 3.3*c)* and *d)*, and so although the definition of convergence as defined in [5] was not met the authors decided to stop the analysis at 2000 trials since the best 20 GOF values had already stabilized at that point. It can be seen that, for the Simple case, this equals an over-night simulation time (ca. 14 hours).

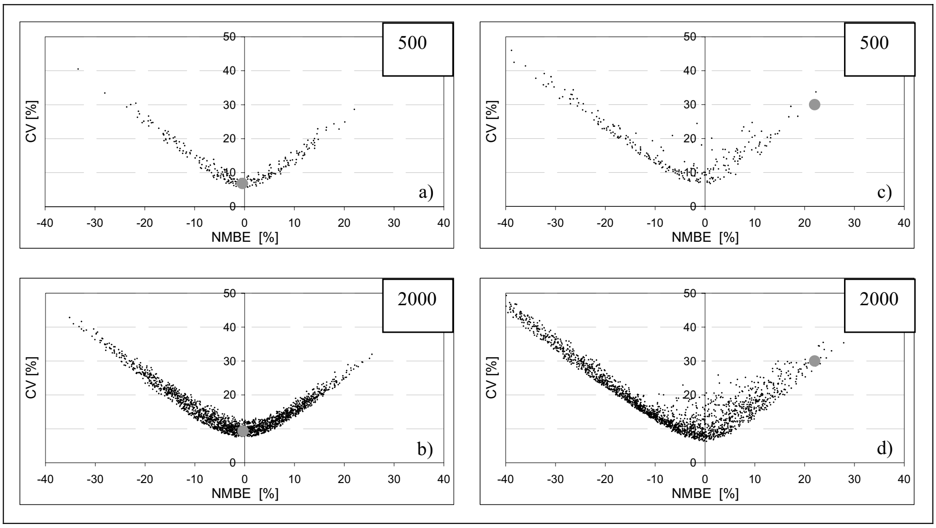

Figure 3.3 ***a)*** **Detailed, 500 Simulations;** ***b)*** **Detailed, 2000 simulations;** ***c)*** **Simple, 500 simulations;** ***d)*** **Simple, 2000 simulations. The grey dot indicates the manually calibrated solution for the Detailed case and the original best guess for the Simple case.**

It can be seen that while the original "best guess" combination of parameter values used for the Simple model generated a poor solution, this model cannot be said to be entirely non-calibrated. Indeed, the original values for the temperature independent loads (lighting, equipment and hot water), the choice of what parameters to include in the Monte Carlo analysis, and the ranges of variability for their values, were determined during the process of calibrating the Detailed model. Had other ranges of variability or parameters been considered the results would likely have been worse. Hence, the Simple model should be regarded as a semi-calibrated model rather than a completely uncalibrated one.

The comparison of simulation results against the measured utility data is shown in Figure 3.4; both energy and power are plotted, in weekly series for the Detailed model, *a)* and *b)*, and in monthly series for the Simple model, *c)* and *d)*. The black line represents the measured data, the grey line the original solution and the dashed line the candidate solution with the best GOF value.

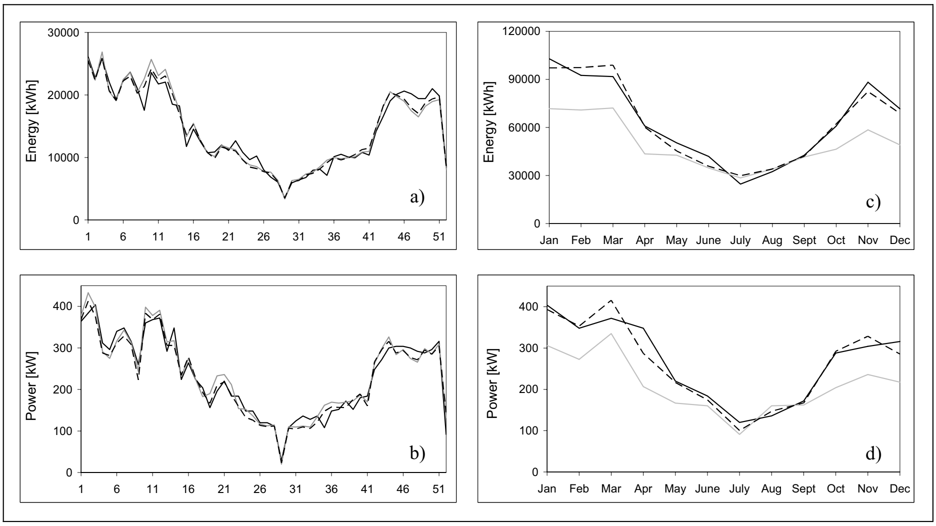

Figure 3.4 **Energy and Power graphs showing measured (black), best (dashed) and original (grey) results. *a)* Detailed energy; *b)* Detailed power; *c)* Simple energy; *d)* Simple power.**

The overall results for both Detailed and Simple models with 2000 trials are shown in Table 3.2; both are simulated for the reference year 2006. Additional results are presented for the Simple model simulated for years 2004 and 2005, as well as results for the optional steps of the fine grid search and parameter freezing.

Table 3.2 **Comparison between original solutions and top 20 candidates from the 2000 trials.**

Case	Original solution					2000 trials		2000 trials - top 20 candidates		
	Energy		Power		GOF	candidates found	strong parameters	coarse grid	fine grid	freezing
	NMBE	CV	NMBE	CV				GOF	GOF	GOF
Detailed weekly	0 %	9 %	-1 %	9 %	6.65	437	p7, p14	5.91 - 6.40	---	6.15 - 6.42
Detailed monthly	0 %	7 %	-2 %	8 %	5.46	451	p7, p14	4.54 - 5.18	4.38 - 5.11	5.01 - 5.30
Simple	22 %	30 %	22 %	28 %	25.60	127	p5, p7, p14, p15	6.33 - 7.36	6.24 - 7.10	---
Simple 2005	40 %	44 %	34 %	39 %	39.22	7	p7, p15	8.56 - 9.28	8.54 - 9.24	---
Simple 2004	41 %	44 %	34 %	37 %	39.11	48	p7, p9, p11, p13, p15	8.47 - 9.23	7.99 - 8.79	---

The Simple model shows a great improvement from the original solution, prior to Monte Carlo analysis, to the best solution, as indicated in the graphs of power and energy in Figure 3.4. This is reflected by the fact that the GOF is significantly improved from the original value of 25.60 down to 6.33. A similar behaviour can be seen for 2004 and 2005; even though the model was not calibrated at all for these years (temperature settings and schedules were different, as observed in the Introduction, but also the main ventilation fans were changed in 2006) there is a great improvement from the original solution. However, in these cases the best GOF values are around 8 or 9 rather than 6 or 7, and in 2005 only 7 candidates are found.

The data in Table 3.2 also indicates that the main heat exchanger efficiency (p7) and the schedules (p15) were the only two parameters identified as strong for all of the cases[3]. The temperature settings (p14) appeared as strong in multiple models, while the infiltration (p5), specific fan power (p9), main ventilation flow rate (p11) and internal gains (p13) all appeared as strong in one of the four cases.

The authors also explored the potentials of two optional steps, see Figure 3.2. In the Detailed case the parameters that appeared as strong after 2000 simulations were frozen at their dominant values and an additional batch of simulations was run. This resulted in the identification of further strong parameters, but as a drawback also produced poorer (increased) GOF values, as shown in Table 3.2. The fine grid search, instead, resulted in only minor improvements in the GOF values for each of the four cases, again shown in Table 3.2.

The focus of this work was on the identification of multiple calibrated solutions, but their application to the estimation of Energy Conservation Measures (ECMs) was also performed through a simple example where the efficiency of the heat exchanger in the main building was increased to 75%. This was applied to all of the top 20 candidate solutions for both the Simple and Detailed models. The results are shown in Figure 3.5, where the variation in energy demand is plotted on the *x*-axis while the GOF values are used to sort the results in the y-axis. The median value gives the central estimation of the expected energy savings, while the standard deviation can be used to express the uncertainty of such estimation. If the randomness of results is assumed to be normally distributed it can be said that within a statistical interval of confidence of 95% (twice the standard deviation) the analyzed ECM is expected to reduce energy consumption by 14.4% ± 1.4% in the Detailed model, and by 10.5% ± 2.4% in the Simple model.

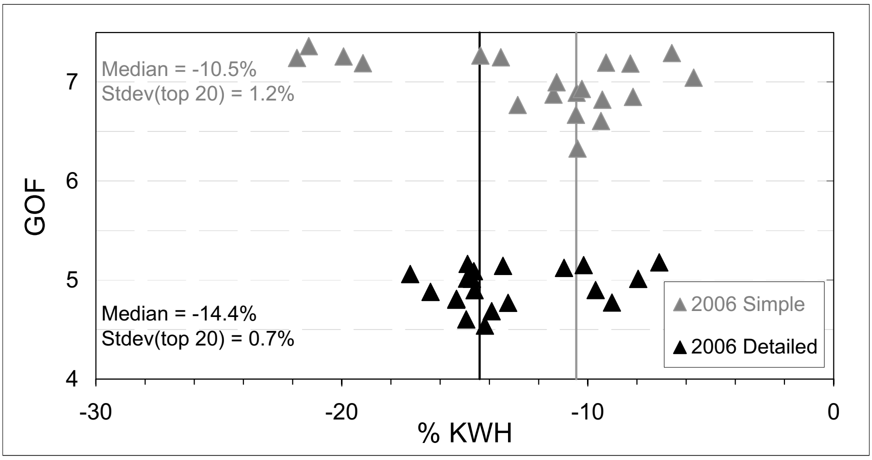

Figure 3.5 **kWh % variation for the ECM in the top20 with median and standard deviation.**

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[3] p15 is excluded from the Monte Carlo analysis of the Detailed model because its value is known with precision in 2006.

3.5 Conclusions

The proposed procedure is of interest because it has the potential to identify multiple calibrated solutions for a more robust analysis of energy saving measures and to save time in developing calibrated models. In this study the manually calibrated Detailed case resulted in an improvement in the fit between simulated and measured data, as well as the identification of the desired 20 candidate solutions. Similar results were observed also for the semi-calibrated Simple case; the fit between simulated and measured data in this case was less accurate but still largely within the limits defined in [6]. The stabilization of strong parameters is suggested in [5] as the guidance to determine the number of simulations to be run; here, this was found insufficient. No definitive criteria were found to unquestionably find the optimal number of simulations for any case. Rather, the number of simulations was empirically recognized by observing the strong parameters, the goodness of fit and the pattern distribution of the solutions. Optional steps like the freezing of strong parameters or the fine grid search showed here to bring about only non-critical benefits.

In the interest of applying this method in the energy simulation of buildings it is the suggestion of the authors that a semi-calibrated model should be developed and iteratively calibrated through the identification of strong parameters and the gathering of data. This ensures that the most effort will be exerted in defining those inputs that are most critical to the results of the simulation, while not spending excess time in performing a detailed manual calibration.

3.6 References

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Case study on retrofit of a Norwegian school: possible to achieve the passive house standard?

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4 Case study on retrofit of a Norwegian school: possible to achieve the passive house standard?

4.1 Abstract

The energy demand of an existing school building is simulated with a dynamic software tool using a model calibrated against metered data. A series of retrofit measures are simulated in order to achieve the performance requirements for passive house standard for school buildings. The implemented energy saving measures are grouped into the following sets: controls, lighting, ventilation, windows, insulation and additional measures to fulfil the passive house definition. The order of their implementation is meant to represent an increasing level of complexity for the operations to perform. The results show the incremental effect of each set of measures and compare it to the equivalent energy class achieved. The cumulative effect of all the measures allows to meet the passive house requirements on both net heating energy and total primary energy demand. Particular attention had to be dedicated to the retrofit measures for the ventilation system.

4.2 Introduction

The building used in this case study is the Steindal elementary school, located in Trondheim, Norway (Latitude: 63°36'; Longitude 10°23'). The purpose of this work is to analyse, with the aid of computer simulations, what measures are necessary to undertake in order to achieve the passive house standard for this school building. The Steindal School serves some 340 students and 40 administrators. The main building was built in 1978, with an additional wing, or annex, constructed in 1997; the total area is ca. 4800 m^2 divided between two floors. The school is located on the top of a small hill and is characterised by a glazed façade on the north side, as visible in Figure 4.1*b)*, while in the south side the lower storey is under ground level because of the hill's slope.

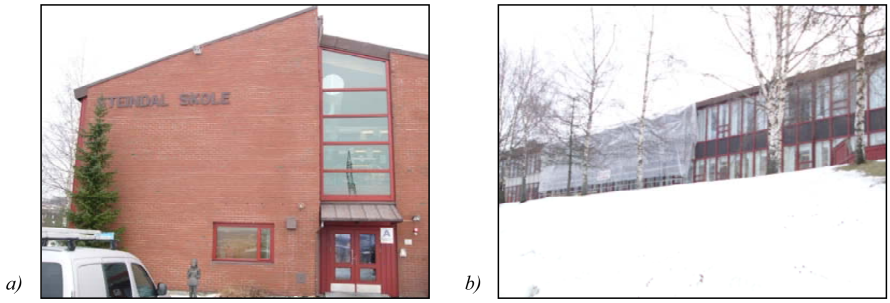

Figure 4.1 **Steindal school *a)* west façade, and *b)* north glazed façade.**

Outdoor air is supplied by two balanced ventilation systems with heat recovery, one in the main building and one in the annex, while heating is supplied locally in each room by electric resistance radiators; the building has no cooling system. Ventilation air in the annex is heated to the supply temperature (18°C) by an electric coil, while in the main building the heating coil is supplied with hot water produced by an electric boiler.

Electricity is then the only energy carrier used by the school, and hourly data on metered consumption are available from the local electricity company. The cumulative energy consumption is presented in Figure 4.2 and shows a significantly lower consumption in 2006 and 2007. While the differences between years 2002 to 2005 are mainly due to temperature differences, the gap registered for 2006 and 2007 is predominantly the result of changes in the schedules of operation and temperature settings made by teachers and students of the school in the context of a communal programme aimed to teach and promote energy savings.

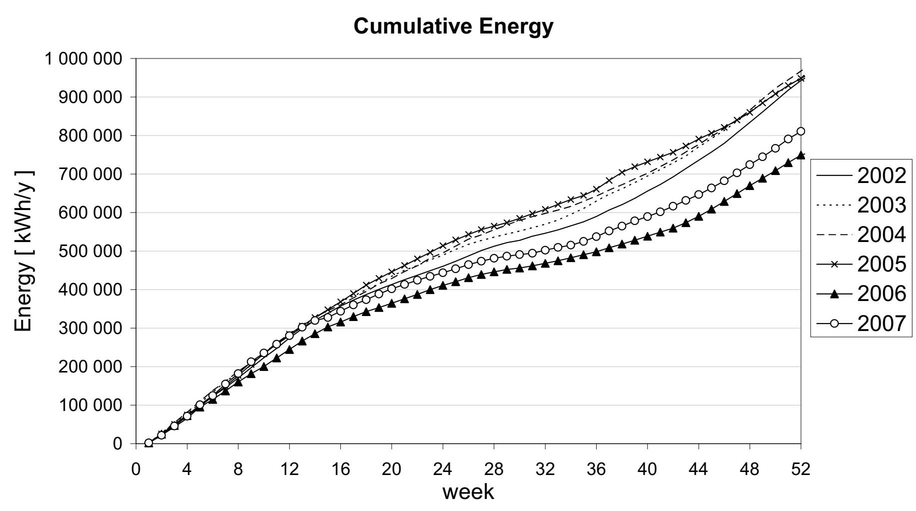

Figure 4.2 **Energy consumption from 2002 to 2007.**

All the temperature sensors and other controls in the school are remotely connected to a control room in the local municipality, from where all the settings can be made. The programme was initiated in 2006 and the energy saving initiatives included mainly a reduction of operating time for the ventilation system and the temperature settings in the locals. The ventilation system in the main building serves locals with diverse occupancy schedules, as offices, classrooms and the gym. Because the gym is normally used once or twice per week in the evening by local sport associations or music bands, the ventilation system was on until late in the evenings. After the energy saving program began the ventilation system stops at 16:00h and is eventually switched on again only in the evenings of occupancy. Ventilation starts at 6:00h in the morning in order to assure clean air in the locals by the time occupancy begins, around 7:30h. The temperature in classrooms and offices were set to be between 20-21°C instead of the previous 23°C or higher settings. However, the somewhat higher consumption in 2007 may be partly explained by an increase in the temperature settings for some of the classrooms, as some teachers had lamented the locals to be too cold [Steindal, 2006]. Besides, it should be borne in mind that in the offices it is possible to manually adjust the temperature settings.

4.3 Method

Data was gathered from technical drawings, documentation, site visits to the school with the caretaker and meetings with building managers and architects. The Trondheim municipality provided ventilation and temperature setting data from their remote control centre. Drawings and documentation were obtained from the school, and conversations with building managers and architects provided further information about the construction. Dialogue with school teachers and administrative staff provided detailed information on occupancy schedules. The building was modelled using “EnergyPlus”, a dynamic simulation software [Energy Plus, 2006]. For modelling purposes the school was subdivided into seven thermal zones; six of them are shown in Figure 4.3, the seventh being the under-roof unheated buffer space.

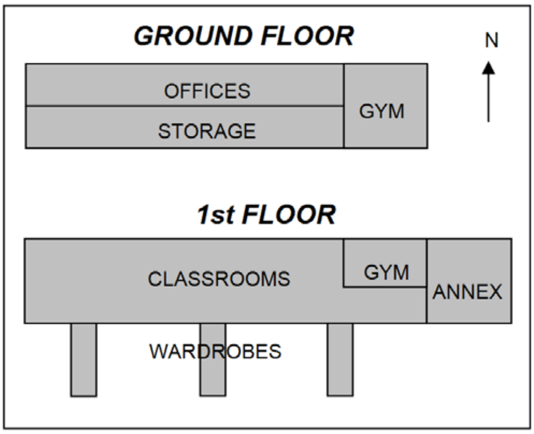

Figure 4.3 **Floor plan of the school.**

The energy consumption has been simulated and the computer model was calibrated against metered energy consumption for year 2006. The calibration procedure is explained in the detail in a previous work, [Sartori and Ricker, 2007]. In simulating buildings' energy consumption there is always an intrinsic uncertainty with which it is possible to know the many required parameters. The calibration was performed both manually and with the support of a Monte Carlo method, in an attempt to obtain a more robust model. The Monte Carlo method revealed helpful for the calibration process, allowing identification of the most critical parameters and improving the overall goodness of the model. In addition it allowed identifying a set of top-twenty calibrated solutions obtained by different combinations of the parameters and all satisfying predefined criteria. The rationale for this was that it would help when trying to asses and compare the potential effect of alternative energy saving measures, because the results would be less affected by the uncertainties on the input parameter values. Nevertheless, in the work presented here the purpose is to apply a set of modifications to the model, one on top of the other, until the passive house performance is eventually achieved. The final building will then be completely different from the original one in all its major parameters (as U-values of envelope parts, properties of the ventilation system and so on). Hence, it is not interesting here to keep on working with the set of top-twenty calibrated solutions, because this would not add useful information in this case. Only the manually calibrated model is used here; it shall be reminded that manual calibration – by means of tuning the values of those parameters identified as more important until a satisfactory match with metered data is achieved – is the conventional way of performing calibration in building energy simulation.

Besides, the base model used here to represent the school building in its actual status slightly differs from the one presented in the above mentioned paper, due to a few details. A closer analysis to the energy demand of the building and further talk with technical personnel allowed understanding the nature of some baseload – a load present also out of occupancy time – that before was not fully understood. Basically, the gym's cloakroom and the cloakroom s in the first floor are heated by means of a floor cable system that is manually regulated, hence out of the remote control centre in the municipality. Again, both metered data and results from simulations are on an hourly basis; but when grouping up the data to monthly figures, this can be done in slightly different ways. In the previous work a month was considered simply as the sum of 720 hours, while here the months have been considered with their actual length. For these reasons the graphs shown in Figure 4.4 are somewhat different from those presented in [Sartori and Ricker, 2007]. The statistical indicators that quantify the ability of the model to reproduce the metered results are nearly unchanged. For a full explanation of the statistical indicators and their meaning reference is made to [Reddy and Maor, 2006].

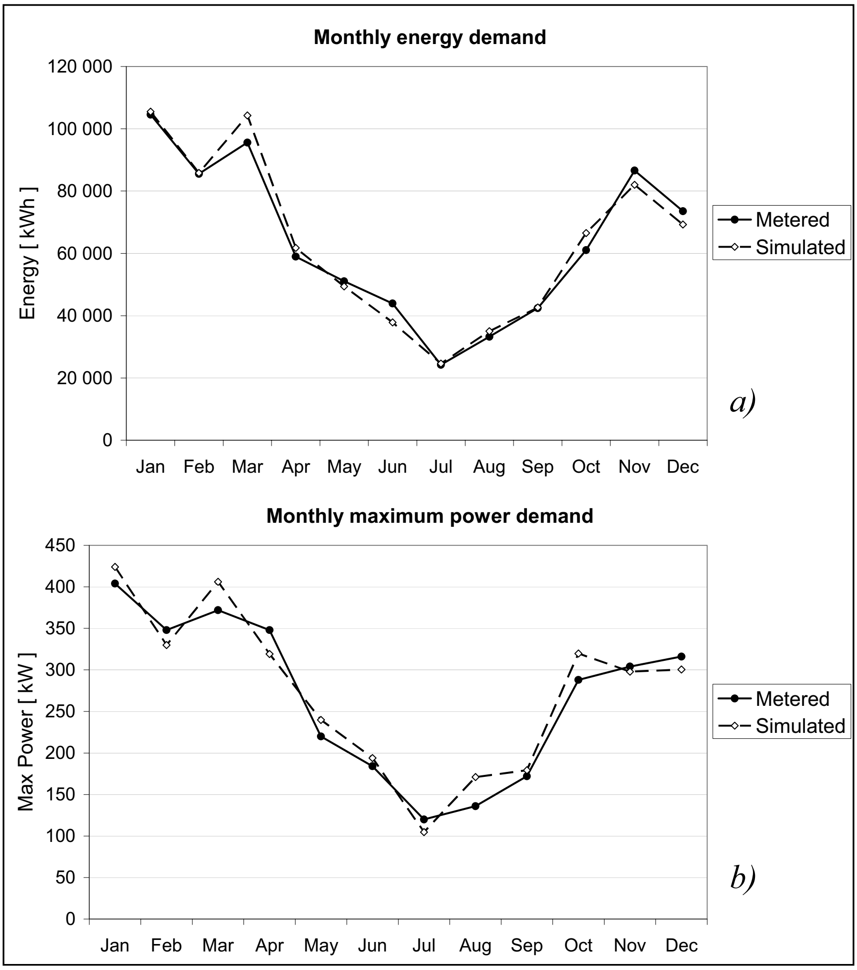

Figure 4.4 **Metered vs. simulated monthly values for *a)* Energy and *b)* Power.**

Another way to compare the simulated results against the metered consumption is to plot them on a time series graph as shown in Figure 4.5. Similar plots were used during the calibration process to help understanding the behaviour of the simulation model and its similarity or non- with the metered data series. Metered and simulated data are plotted in blue and yellow respectively, and the outdoor temperature (dry bulb) is also plotted in brown, so that correlations between temperature and energy demand can be observed. The graph shows a segment of the yearly hourly series, corresponding to a week in March. The peaks in energy demand corresponds to daily occupation time, when ventilation, lighting and other equipment are on. The valleys, on the other hand, correspond to nights and weekends when the school is not occupied and the temperatures are set back a couple of degrees. It can be seen that while an evening of gym occupancy was simulated on a Wednesday it actually took place on a Thursday; but this will not affect the overall result when calculated on monthly or yearly basis. It is also possible to notice the correlation between outdoor temperature and energy demand; when the former decreases the latter increases.

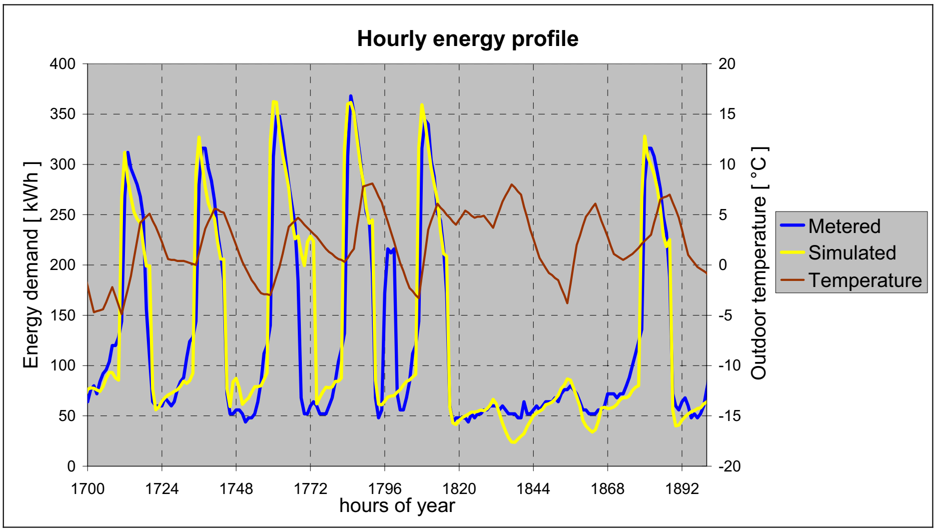

Figure 4.5 **Segment of hourly time plot for energy demand and temperature.**

4.4 Results and discussion

The calibrated model of the school building has been modified by changing some parameters according with the kind of intervention simulated. The areas of intervention were grouped up in: controls, lighting, ventilation, windows, insulation and other changes necessary to comply with the passive house standard. The changes were applied in sequence and with a cumulative effect. The order of their implementation is meant to represent an increasing level of complexity for the operations to perform; hence the order is likely to represent also an increasing cost for the kind of intervention, even though costs are not explicitly addressed in this paper. The list of interventions, or set of measures for energy saving, is shown in Table 4.1 with a summary of the parameters that have been modified and their values before and after the intervention respectively. The corresponding results are shown in Figure 4.7. It can be seen that none of the measures contemplates reduction of energy for equipment, even though some reduction could be assumed due to more energy efficiency appliances in the offices, computer lab and kitchens (refrigerators and so on). Also, it is not considered necessary to introduce an active cooling system; the pupils are not at school during summer, and simulations of natural ventilation through window openings showed sufficient to keep comfortable temperatures in the north facing office area of the building.

The ultimate goal of the energy saving measures is to achieve the compliance with the passive house standard for a school building, as defined in [Passivhaus-Schulen, 2006], which is a collection of works on school projects culminating with the definition of design criteria. The major requirements are the same as for residential buildings: a net heating demand not higher than 15 kWh/m^{2}y and a total demand expressed in primary energy units not higher than 120 kWh/m^{2}y.

Table 4.1 Parameter settings for the energy saving measures.

Set of measures	Parameters modified	Before	After
Original[a]	Weather file:	Trondheim 2006	Oslo Typical Meteorological Year
	Temp. settings in classrooms:	20 / 18 °C	21 / 19 °C
Controls	Heating in cloakroom s and storage area (18°C):	Manual, power regulation	Automatic temperature regulation
Lighting	Power in use during occupation:	57 kW	29 kW (~50%)
Ventilation	Ventilation type:	Centralized (Main build.)	Zone by zone
	Ventilation rate during full occupation:	~ 46 000 m^3/h (3.5 ach)	~ 25 000 m^3/h (1.9 ach)
	Heat recovery efficiency:	55%	80%
	Specific Fan Power:	Main 2.9, Annex 1.6 kW/(m^3/s)	All 1.3 kW/(m^3/s)
Windows	U-value glass:	1.9 – 3.3 W/m^{2}K	0.8 W/m^{2}K
	Solar Heat Gain Coefficient (g-value):	0.39 – 0.78	0.5
	U-value frame:	1.5 W/m^{2}K	0.7 W/m^{2}K
	Zone infiltrations:	0.1 – 0.3 ach	0.1 ach
	Temp. settings:	21 / 19 °C	20 / 18 °C
Insulation[b]	U-value walls:	0.31 W/m^{2}K	0.1 W/m^{2}K
	U-value roof:	0.19 – 0.28 W/m^{2}K	0.07 + ΔU = 0.03 W/m^{2}K
	U-value ground floor:	0.67 – 1.44 W/m^{2}K	0.20 + ΔU = 0.06 W/m^{2}K
	Ground temperatures:	14 – 16 °C	9 – 11 °C
	Zone infiltrations:	0.1 ach	0.05 ach
Passive House	Heating source priority:	Room heaters	Ventilation air
	Hot water production[c]:		
	• Source	Electricity	Natural gas
	• Efficiency	90%	85%

[a] with respect to the model in [Sartori and Ricker, 2007]
[b] ΔU are due to thermal bridges
[c] also for the heating coil in the ventilation system

The original building is simulated here using climate data from a typical meteorological year for Oslo rather than year specific data for Trondheim. This is done with the intention to represent a standard situation, since in [Wigenstad et al., 2005] the Oslo climate is prescribed to be used as the reference climate for assessment of building's energy class, in accordance to the European Directive on Energy Performance of Buildings (EPBD). The temperature settings in the classrooms are one degree higher than in 2006; again, this is done to represent a standard situation as the setting of 21°C – and 19°C in setback – is prescribed by the Norwegian norm for calculation of energy requirements [NS3031, 2007]. Also, it is likely that as explained above the temperature in the classrooms have been set to higher reference values after 2006 for reasons of comfort. In these operating conditions the energy demand for the original building amounts to 183 kWh/m^{2}y. According to the classes definition given in [Wigenstad et al., 2005] this school building belongs to the class E (161-190 kWh/m^{2}y), which is supposed to be the energy class representative of the average condition of today's stock. This fact is particularly interesting because it allows considering this case study as representative of an average situation in the stock of existing school buildings.

The heating in the storage/workshop locals and in the cloakroom s is controlled by manually selecting the operating power of the heaters or floor cables. It has been observed that in this way the rooms were heated more than necessary, and also that heating was generally on also during weekends and periods of vacation (when the setback should be 14°C), and to some extent also during summer ([Steindal, 2006]). Substituting the manual control with an automatic one and optimising the temperature settings and the schedules allows to reduce the energy demand to 163 kWh/m^{2}y, which is still in the range of the energy class E but close to the limit of class D; in Figure 4.7 this is emphasized by the label ”E+”.

The next intervention consists in substituting the light tubes and light bulbs with energy efficient ones. It is estimated that such change has the potential to nearly halve the energy demand for lighting. Nevertheless, as lighting is also a source of internal gains, reduction of lighting energy is accompanied by an increase in heating energy to compensate for the diminished internal gains, at least during the heating season. The overall effect in reducing heating demand is small and it results in a figure of 159 kWh/m^{2}y, equivalent to a class D (131-160 kWh/m^{2}y).

Intervention on the ventilation system involves changing several parameters. The new system (unique for all the school) is supposed to be operated zone by zone, according to the occupancy schedule. The system can be still centralized, but in contrast with today’s on/off functioning, the fans can be operated at variable speed and the zones can be included or excluded by means of automatically controlled dampers. If necessary, two fans can be used in parallel to supply the maximum required flow but allowing a wider range of reduced flow operation as one of the two can be switched off when needed (variable speed fans have a lower limit on the fraction of nominal speed at which they can operate). The system ducts and components are supposed to offer low pressure drop, so that low pressure and high efficiency fans can be used, resulting in an overall Specific Fan Power of 1.3 kW/(m^3/s) instead of the actual 2.9 in the main building and 1.6 in the annex.

Today’s heat recovery units are a cross flow in the annex and a rotary wheel in the main building. Real time data obtained by the remote control centre at the municipality revealed some anomalies in the operation of the rotary wheel. Probably due to some problems with the control logic the wheel was found to operate often at its minimum allowed speed (like a “safety mode”) instead of its nominal speed. This inconvenience may be the cause of a reduced efficiency of the heat recovery unit that should warranty 75% temperature efficiency according to label data; besides, the rotary wheel is still the original one from 1978. However, the calibration process performed in [Sartori and Ricker, 2007] with the help of the Monte Carlo method suggested a value of 55% as most probable actual efficiency of both systems, in the main and in the annex buildings. The new ventilation system has a heat recovery unit with an efficiency of 80%.

The maximum ventilation flow rate, when all the zones are served, is also reduced; the reason for this requires some more explanation and Figure 4.6 will serve the purpose. The required ventilation rate is defined in relation to the occupancy intensity, or level, in the locals expressed in persons per square meter. The guide to the Norwegian technical norm of the building code [TEK VEIL, 2007] says that in order to guarantee desirable levels of air quality a certain air flow rate has to be supplied to compensate for emissions from both occupants and materials. About materials three levels are defined: low-emitting, normal and undocumented materials, with corresponding air flow rates of 0.7, 1 and 2 l/s/m^2. About persons a flow rate of 7 l/s per person shall be supplied; the central issue is how to determine the occupancy level. The same [TEK VEIL, 2007] offers a table of maximum occupancy for different kind of locals, specifying that where available actual data on occupancy shall be used in place of those provided by the table. The differences between maximum occupancy and real occupancy are significant. For example, for a school the maximum occupancy is set to 2 m^2 per person while the actual occupancy of the first floor of Steindal school, where the classrooms are, is about 6.5 m^2 per person. The maximum values are safety values meant to guarantee good air quality with a large margin; they could be correct values for example for a closed teaching room with high density of pupils, but it is not justifiable to adopt the same value for an entire zone that also comprises playrooms, corridors and a number of spaces dedicated to various activities other than frontal teaching.

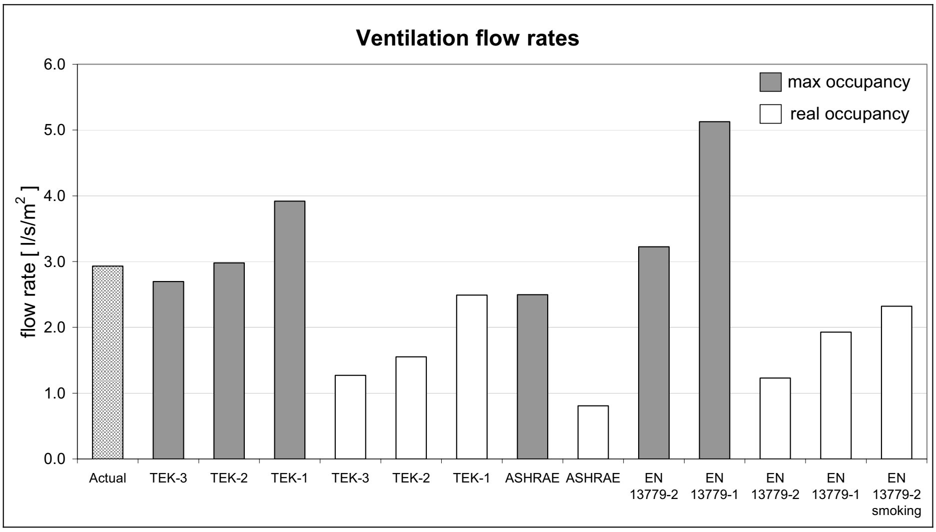

Figure 4.6 **Various flow rates according with different codes and occupancy levels.**

The actual occupancy of Steindal school was estimated for the different zones and the resulting total ventilation flow rates expressed in l/s/m^2 are shown in Figure 4.6 in white; in grey are the corresponding values for a maximum occupancy. The labels 'TEK-' refers to the Norwegian norm when considering low-emitting, normal and undocumented materials, respectively. Results for other codes than the Norwegian are also shown for comparison. The American [ASHRAE, 1999] and the European [EN 13779, 2007] norms define their own reference levels of maximum occupancy; again, the graph shows resulting flow rates for both maximum and real occupancy. The European norm defines four levels of air quality; here only the highest two were considered, and they are labelled '-1' for "very-good" air quality and '-2' for "good" air quality. Generally a level '2' is sufficient for both office and school spaces. It is worth noting that the actual ventilation flow rate used in Steindal school, that roughly corresponds to a 'TEK-2' indication with maximum occupancy, is higher than the flow rate prescribed by the European norm for a room of air quality level 2 ("good") in presence of smokers (see "EN 13779-2 smoking" in Figure 4.6).

The value chosen for the energy saving measures on the ventilation system is the 'TEK-2' with real occupancy data, meaning an average of 1.6 l/s/m^2 corresponding to approx. 25 000 m^3/h for the entire building versus the today's 46 000 m^3/h. The value for the classrooms area is equivalent to 48 m^3/h/pers and is about the double than the value suggested in [Passivhaus-Schulen, 2006] and also reported by [Weiss et al., 2006], where monitoring projects of CO_2 concentration showed that a flow rate of about 15-25 m^3/h/pers is generally enough to meet (European) regulation requirements on air quality. Altogether the changes on the ventilation system bring the energy demand down to 107 kWh/m^{2}y, which means in class C (101-130 kWh/m^{2}y) but close to reach the class B performance; in Figure 4.7 this is emphasized by the label "C+".

Windows are an important building element in general, but especially for this school building where the entire north façade is covered by glazed area. Different types of windows are installed at the present in the building. The north façade of the main building still has the original old windows from 1978, and part of them (those operable) were being replaced in 2007, see Figure 4.1*b)*. Other windows in the south façade have been replaced in the meantime and windows in the annex are newer, from 1997. The U-value of installed windows and glazed areas varies from 3.3 to 1.9 W/m^{2}K; corresponding estimated values of solar heat gain coefficient (g-value) and U-value for the frames are reported in Table 4.1. All windows and glazed surfaces are substituted with windows that satisfy the passive house criteria. They have a U-value of 0.8 W/m^{2}K, insulated frame with U-value of 0.7 W/m^{2}K and g-value of 0.5 (e.g. a triple pane window with clear glass and double low-e coating). In addition, it is supposed that substituting the windows also the air tightness of the building results improved. In facts, it has been observed during the works of substitution of some of the north face windows that the conjunction between wall and window frame was poor (e.g. loose and with no insulation at all along the frame's perimeter). As a consequence it was estimated that by substituting the windows the infiltrations are reduced to a value of 0.1 air changes per hour (ach) in all zones, from the actual 0.1-0.3 ach depending on the exposition of the zone. Finally, adopting high performing windows the temperature of the innermost pane increases, so that the difference between room air temperature and mean radiant temperature is small and the same operating temperature (the average of the two) can be achieved also with lower settings. Hence, room air temperatures are set to 20°C, and 18°C during night and weekend, in all office and classroom zones. As an overall result the total energy demand gets down to 65 kWh/m^{2}y, achieving the performance of a class A school building ($\leq$ 65 kWh/m^{2}y).

Wall construction, for the major part, is made of two layers of brick encapsulating a layer of about 15 mm of mineral wool. Walls against ground in the storage rooms are made of concrete only, with a thickness of 50 cm. The roof is also insulated with mineral wool while the ground floor has only a perimeter insulation layer made of EPS. The corresponding U-values are reported in Table 4.1. For the intervention on insulation it is assumed that walls can be covered by cladding-on insulating blocks as those used in the renovation of the Schwanenstadt high school in Austria [Gasser and Plöderl, 2007].

Because the extra insulating layer is applied on the exterior of walls, the thermal bridges on the wall constructions can be neglected. In the case of roof, ground floor and walls against ground, instead, additional internal insulation improves the structure's U-value but also presents thermal bridges. The thermal bridges are estimated according to [Hauser and Stiegel, 1994] and their values are reported in Table 4.1. Increasing the insulation of the envelope elements that are in contact with the ground also reduces the heat dispersed and in turn reduces the average temperature of the ground surrounding the building. The monthly average values for the ground temperature underneath the building are then changed from the initial 14-16°C to the 9-11°C after improving the envelope's insulation. Ground temperature values have been estimated using the software [PHPP 2007]. Again, the air tightness is assumed to improve due to the extra insulation and reach levels that comply with the passive house standard of 0.6 ach under a pressurisation of 50 Pa ($n_{50} \leq 0.6$ Pa with blower-door test). At normal operating conditions this value is assumed to correspond to infiltrations of $n = 0.05$ ach for all zones; the conversion between n_{50} and n is calculated according to [NS3031, 2007]. The effect on total energy demand is to reduce it down to 48 kWh/m^{2}y, abundantly below the requirement for class A, and labelled in Figure 4.7 as "A+".

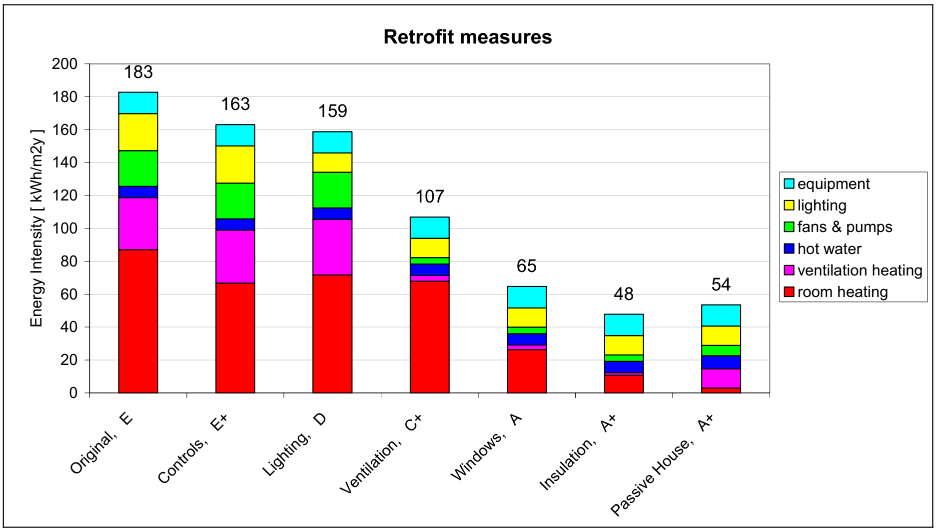

Figure 4.7 **Cumulative effect of the retrofit measures.**

With the implementation of extra insulating measures the goal of reducing heating demand to less than 15 kWh/m^{2}y has been achieved; the sum of room and ventilation heating is actually 13 kWh/m^{2}y in this case. Nevertheless, the requirement on total primary energy is not satisfied. The only energy carrier used in the school is electricity, and according with the German norm [DIN V 4701-10, 2003] the conversion factor from delivered to primary energy for electricity is 2.7. The figure would be different if a Norwegian conversion factor is used, since national production of electricity is almost entirely from hydropower, giving a conversion factor practically equal to the unity. Yet, the electricity market in Nordic countries is now unified in the NordPool power exchange and the tendency is to go toward a unified European electricity market. In this light it is more correct to adopt conversion factors that are valid in a broader context than Norway. Considering the total electricity demand of 48 kWh/m^{2}y and adopting the German conversion factor of 2.7 the figure on primary energy results being 130 kWh/m^{2}y, which is higher than the required limit of 120 kWh/m^{2}y. To overcome this inconvenience it is possible to assume another energy carrier being used for heating purposes in the building. As an example it was chosen to use natural gas; even though a natural gas network is not developed in Norway the choice is justified for an exemplification case because natural gas has a conversion factor of 1.1 that is worse than other alternative carriers as district heating (0.8) or wood (0.2). In the "Passive House" measures, ventilation air becomes the prioritised source of heating (with an upper limit of 50°C in the supply air) while room electric radiators are used only to cover peak loads and to help preheating the locals after the weekends. The heating coil in the ventilation is now supplied by hot water from a gas boiler with an overall efficiency (including transmission losses) of 85%. Also the hot water for domestic purposes, as hot tap water in the kitchens and showering in the gym's showers, is produced by the gas boiler. Cooking is supposed to remain electricity based. Altogether the building requires now some more energy for heating (15 kWh/m^{2}y) and also in total (54 kWh/m^{2}y) because of the lower efficiency of a gas based heating system. On the other hand, the energy used for ventilation heating (12 kWh/m^{2}y) and for hot water preparation (8 kWh/m^{2}y) is now converted into primary energy through a smaller factor. The total primary energy demand results in 114 kWh/m^{2}y, and the definition of a passive house school building is then fully met.

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Modelling energy demand in the Norwegian building stock: scenario analysis based on activity flows, energy class and user preference

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5 Modelling energy demand in the Norwegian building stock: scenario analysis based on activity flows, energy class and user preference

5.1 Abstract

A model has been developed for studying the effect of three hypothetical policies in reducing electricity and energy demand in the Norwegian building sector. The policies aim to maximize diffusion of thermal carriers, heat pumps and conservation measures respectively. Combinations of these are also considered. The model has a demand side perspective, considers both residential and service sectors, and calculates energy flows from net to delivered energy. Energy demand is given by the product of activity and intensity matrices. The intensity properties are defined in archetypes, and are the result of different energy class and user preference options. The activity levels are defined for new construction, renovation and demolition flows. The scenarios are shaped by combining the activity flows with different archetypes. The results show that adopting conservation measures on a large scale does allow reducing both electricity and total energy demand from present day levels while the building stock keeps growing. The results also highlight the inertia to change of the building stock, which is a consequence of low activity levels. Regarding modelling issues, the importance of making a clear distinction between the assumptions on intensity and activity levels is discussed.

5.2 Introduction

Energy demand in the building stock in Norway represents about 40% of the final energy consumption, of which 22% goes to the residential sector and 18% to the non-residential sector. Similar figures are reported for the EU countries (DGET, 2004) and are also valid for western countries in general. In Norway, where there is a strong dependency on electricity for heating purposes, electricity covers about 80% of the energy demand in buildings. These numbers reflect the potential for improvements inherent in the building stock. Policies targeting a reduction of energy and electricity demand in the building sector should be based on sound models of the stock and the mechanisms inside it that are ultimately responsible for the energy demand.

Nonetheless, some aspects seem not to be fully understood, and this may represent a significant handicap for policy making. In his work Myhre (2000) makes a thorough analysis of the residential sector in Norway and explores different scenarios for future energy demand until 2030. He considers a number of age groups and a number of retrofit options for the different age groups. However, the hypotheses about the amount of renovation activity seem not to be based upon empirical evidence. Furthermore, possible substitution of electricity with other carriers is not considered.

A scenario analysis is also performed by Johannson et al. (2006 and 2007) for the building stock in a Swedish region, comprising both the residential and non-residential sectors. These studies take a wide perspective on the energy consumption related to the building sector; they analyze the energy flows starting from the buildings' demand and up through the supply chain to finally calculate numbers on primary energy and associated CO_2 emissions. This is surely a worthwhile approach, and the estimation of CO_2 emission is often a most important goal because of the national reduction targets set by the Kyoto protocol. Nevertheless, while these studies embrace in their analysis the entire energy chain, they seem to put the emphasis on the supply side rather than on the demand side. The hypotheses on how changes may happen seem to be based solely on the economic lifetime of heating systems, and the estimation of possible energy demand reduction appears to overlook the inertia that characterizes changes in the building stock. This may have lead to too generous assumptions about the possibility for decreasing energy demand, or at least about its timing.

In relation to this, an interesting work is that of Nässen and Holmberg (2005) on the Swedish building sector. They make an historical analysis of the building stock and the related energy demand in the period 1975-2000, questioning why the total energy use has remained almost unchanged – actually slightly increased – despite the great potential for improvement already known at the time. Nässen and Holmberg (2005) refer to Steen et al. (1981) who had illustrated scenarios for energy demand in 2000 being less than one third of the energy demand in 1975, already achievable with "present known best technologies". Their analysis concludes that because the most prominent measure taken to reduce oil dependence after the oil crises was an increased supply of electricity – through development of nuclear power plants – the potential of improving energy efficiency was poorly utilized. They warn that in a coming transition it will be important to better balance the attention between supply substitution and energy efficiency.

In this work the authors explore modelling energy consumption in the building stock from a demand side perspective. The net energy demand is set as the starting point for the analysis. Energy classes and end-user preferences are defined in order to describe the energy intensity of buildings. In parallel, the amount of floor area related to construction, renovation and demolition activities is also estimated. Intensity and activity data are combined into a scenario analysis aimed at evaluating the potential of three different hypothetical energy policies. Both residential and non-residential sectors are included in the analysis.

5.2.1 Definitions

The energy needed in a building in order to satisfy specific end uses is named *net energy*, as shown in Figure 5.1, and it comprises: heating, cooling, ventilation, hot water, lighting and other electric equipment. Technical systems are used to meet such demand, and the totality of energy delivered to the building site in order to operate all the technical systems is named *delivered energy*.

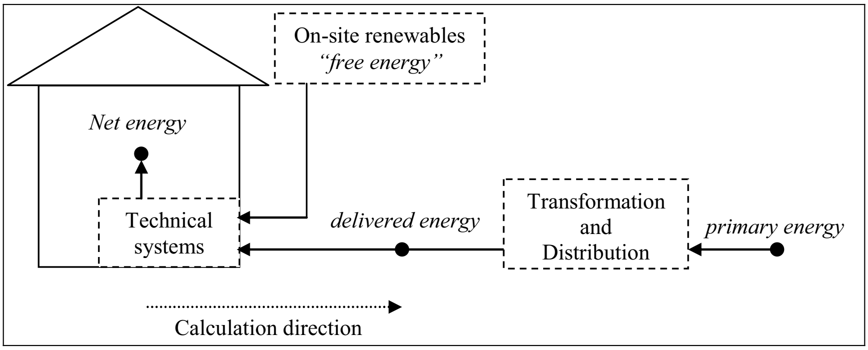

Figure 5.1 Delivered energy as the study object.

The delivered energy is the object of this study. The delivered energy comes in the form of different *energy carriers*, which can be grouped in two main groups: electricity and thermal carriers. The on-site renewable energy is considered as *free energy* in the sense that it is already available to the end user without the necessity to be delivered by any carrier. The calculations performed in this work go from the net energy demand to the delivered energy. Hence, it can be said that the method adopted has a demand side perspective over the energy system and that the model has its boundaries "at the door of the building", leaving out any consideration that goes beyond the delivered energy.

5.2.2 The Norwegian building stock

The energy system in Norway is characterized by the peculiarity of having an electricity production that is for more than 99% based on hydropower (DGET, 2004). The strong hydropower development of the last half century has guaranteed abundant and cheap electricity to the country; electricity has also been accompanied by the image of being environmentally friendly because it is based on a renewable source. These aspects have had a strong influence in shaping the energy demand in Norwegian dwellings (Bøeng, 2005) and in all buildings in general. While the demand continues to grow both in the industrial and the building sector, the further potential for large scale hydropower development is limited due to protection of the remaining natural waterfalls. As a consequence national electricity consumption has increased more than the national power production, and unlike before Norway has actually been a net importer of electricity in the Scandinavian NordPool market six of the ten years from 1996-2005 (NVE 2008). This fact has economical consequences because the imported electricity is more expensive than that produced domestically, and at the same the missed export represents a missed income. Electricity scarcity also poses environmental concerns because imported electricity comes from a production mix with higher CO_2 emissions (in the NordPool market marginal production is especially carbon intensive) and because new gas power plants are being planned to increase domestic capacity. Therefore, there is a strong interest in the opportunities to reduce electricity dependency, and the building sector could play an important role.

The strong dependency on electricity in the Norwegian building stock can be seen when looking at the heating systems installed. According to the last census (Statistics Norway, 2001) about 70% of dwellings are equipped with space heaters and/or floor cables for direct use of electricity, either as the only system or in combination with wood or oil stoves. Only 12% of dwellings have a hydronic system. In total, as much as 93% of respondents state that they use (also) electricity for heating their dwellings. Nevertheless, 70% of dwellings are equipped with more than one heating system, the most popular being direct electricity combined with a wood stove (38%). This means that they can combine electricity with other carriers, at least to cover part of the heating need. The situation is less dramatic in the non-residential buildings, but figures on electricity use are still high. According to data reported by Enova (2006) on about 1900 buildings monitored (of which approx. 1800 non-residential) at least 62% of the service sector buildings have a central heating system, either alone or combined with direct electricity space heaters. Nevertheless, electricity is used in 67% of the cases as one of the fuels also where there is a central hydronic system.

5.3 Method and data sources

The basic concept at the basis of the methodology is that energy demand can be expressed as the product of activity and intensity. The term activity means the amount of building mass, expressed in square meters of floor area, and the term intensity means the energy demanded by a single unit of building mass, so expressed as energy per square meters. Equation (5.1) reports this relation with the appropriate units:

$$Energy\left[\frac{TWh}{y}\right] = Activity\left[m^2\right] \times Intensity\left[\frac{kWh}{m^2 \cdot y}\right] \tag{5.1}$$

where *Energy*, *Activity* and *Intensity* are matrices whose structure is described later. The Intensity matrix is used in two ways: in analysing historical data it is the output resulting by dividing the measured energy consumption by the measured floor area activity. In the scenario analysis the Intensity matrix is an input that multiplies the expected activity in order to forecast the energy demand.

5.3.1 Activity

A number of sources are available on the building stock in Norway, but unfortunately not all the information available is suitable for the purpose of this work. The various sources are analysed in detail in the reports Sartori (2006) and Sartori and Wachenfeldt (2007). The reports conclude that the only suitable source of data is given by the GAB register (Grunneiendom-, Adresse- og Bygningsregisteret), the computer register containing information about ground properties and addresses in Norway. The GAB register contains information on both residential and non-residential buildings, is based on a complete census of buildings, and contains coherent data on the gross area. The only drawback is that the electronic version was established in 1983. Every building is registered in GAB and labelled using a 3-digits code to identify the building categories. The data in GAB need to be read, elaborated and grouped in categories by software before to produce useful information; such software has been developed by the authors and the results have been compared with other sources, when possible, in order to validate the tool (Sartori, 2006). Table 5.1 reports the GAB coding to an aggregated level – one or two digits – and the corresponding building mass in year 2005.

Table 5.1 Data on buildings by year 2005.

Category	GAB code	Share	mass [m^2][a]
Residential sector		**100 %**	**320 829 869**
Farm, single- and row-house	11x, 12x, 13x	80 %	255 069 051
Apartments block	14x, 15x	12 %	40 044 225
Holiday house	16x	8 %	25 716 593
Excluded from the model			
Residential Garage and similar	17x, 18x, 19x		
Industry, Agriculture and Fishery	2xx		
Service sector		**100 %**	**127 116 947**
Office and Shop	3xx	39 %	49 192 584
Transport and communication	4xx	5 %	6 836 984
Hotel and Restaurant	5xx	7 %	8 757 735
Education, Culture, Sport, Religious	6xx	27 %	33 906 419
Hospital and Nursery	7xx	7 %	8 805 852
Prison and emergency preparedness	8xx	2 %	2 466 283
Other	9xx	13 %	17 151 089

[a] gross floor area

The data from GAB had to be aggregated because data on energy consumption are not available at the same level of detail. Two sectors are defined: the *residential sector*, comprising all categories of residential buildings, and the *service sector*, comprising all other categories. A few categories were excluded from the model, either because they have no (or negligible) energy consumption or because their energy consumption is studied separately from the building sector, e.g. being part of the industrial sector. It is worth noting that the residential sector accounts for 71% of the entire building mass.

5.3.2 Energy

The main information on energy consumption comes from Statistics Norway (2007a) that provides data on all the energy carriers from year 1976 until 2005. The statistics provide data for electricity, district heating (from 1991), wood, gas and oil; negligible quantities of charcoal and coke are also reported but disregarded here. The aggregation level is such to allow only a distinction between energy consumption in the residential sector and in the service sector.

Additional information was needed to properly include the effect of heat pumps. This technology is spreading rapidly in Norway, and considering that this trend may continue in the coming years it becomes important to estimate how much heat pumps contribute to satisfy the buildings' net energy demand. The electricity used to operate heat pumps is already accounted for in the national statistics on energy carriers. What is not accounted for is the total amount of heat that is actually delivered to the buildings by heat pumps. It is difficult to make accurate estimates on how much heat a heat pump can provide in usual operating conditions, since this depends on factors such as the kind of heat pump (air-to-air, water-to-air, ventilation heat pump, etc…), its capacity, the number of hours that it operates and so on. Based on the studies by Eggen (2005) and Ground et al. (2007), Wachenfeldt and Sartori (2007) estimate the electricity consumption and the heat supplied by heat pumps in standardized average operating conditions. One key assumption made is that all air-to-air heat pumps are used in the residential sector, while the other types are installed in non-residential buildings. Merging the data from statistics on energy carriers and the estimations on heat pumps results in the data series represented graphically in Figure 5.2. The term *free heat HP* is used to indicate the difference between the heat actually supplied to the building and the electricity required to run the heat pump. The free heat HP is therefore not part of the delivered energy.

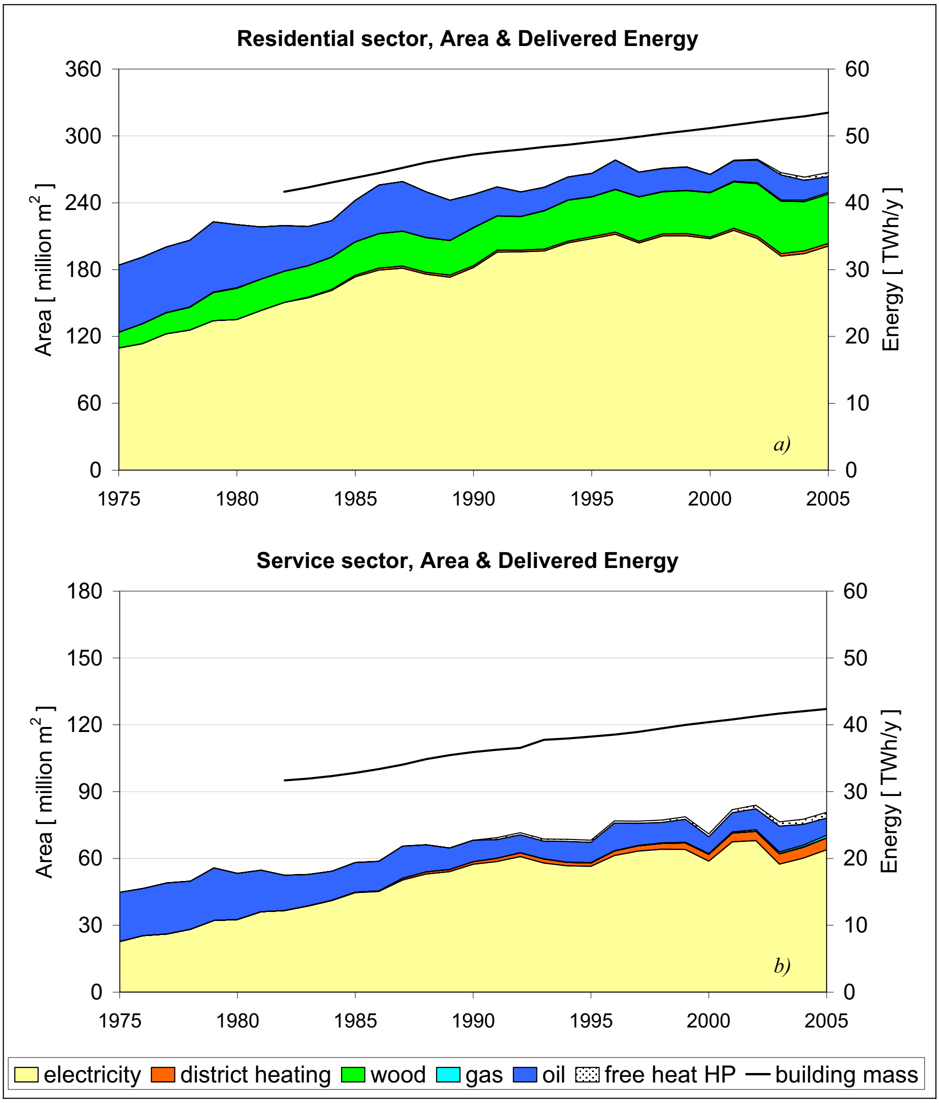

Figure 5.2 **Historical data on area and delivered energy for: *a)* the residential sector, and *b)* the service sector.**

The energy scale is the same in both graphs, rendering visually the comparative magnitude of the residential versus the service sector. The area scale is different; in the residential sector graph it is double that in the service sector graph.

As known, the yearly fluctuations are the result of contextual causes like variable climatic conditions from one year to another (data in Figure 5.2 are not temperature corrected) or price fluctuations for the various carriers. It is clear that there is a linear relation between the size of the stock and the overall energy consumption. As the stock has been growing nearly constantly so has the energy demand, both in the residential and the service sector. In year 2005 the residential sector represents 71% of the entire building mass and is responsible for 63% of the total energy consumption. It is also clear that electricity is the prevailing energy carrier in both sectors. In the residential sector wood has become the largest thermal carrier as the use of oil has slowly decreased. District heating has found only a marginal diffusion and the gas share is so small as to be barely visible in the graph. The contribution of heat pumps is recent and remains small even though rapidly growing. In the service sector oil seems to be phasing off more slowly while wood is not important at all. District heating has grown considerably in the last two decades while the gas share has remained marginal. The diffusion of heat pumps started earlier than in the residential sector and it is hence more pronounced.

5.3.3 Intensity

The sources of information used to gather data on the intensity are the reports from Pettersen et al. (2005) and Wigenstad et al. (2005), subsequently modified by Thyholt et al. (2007). These provided the basis for the revised building code (TEK, 2007). Pettersen et al. (2005) and Wigenstad et al. (2005) describe a methodology that should constitute the basis for the Norwegian classification of buildings based on their energy performance – the Norwegian implementation of the European Directive on Energy Performance of Buildings (EPBD, 2002 and accompanying standards). The methodology is based on both the evaluation of average performance for the present stock, named stock reference R_s, and the prescribed performance for new and largely renovated buildings, named regulation reference R_r. The stock references are obtained through collection of the best available monitoring data and estimations. The values of R_s and R_r are specified for a number of building categories; for new construction indicative numbers are available also for the different end uses, calculated under standardized reference conditions (Thyholt et al., 2007). Estimations for holiday house consumption are taken from Wachenfeldt (2004). The values are reported in Table 5.A1 in Appendix 5.A. The values of R_s and R_r are central to the definition of the energy classes given in the EPBD. The energy classes are labelled with letters from A to G, where A means most efficient and G means least efficient. The Norwegian scale proposed in Pettersen et al. (2005) and Wigenstad et al. (2005) is modified with respect to the European scale (EN 15217, 2007); both scales are reported in Table 5.2. The class 'A+' is reported in parentheses because it is not defined in the EPBD, but it is defined here because that class is also used in this study.

Table 5.2 Definition of energy classes.

Class	EN 15217 scale	Modified Norwegian scale
(A+)	Passive	Passive
A	$\leq 0.5 \cdot R_r$	$\leq 0.5 \cdot R_r$
B	$\leq R_r$	$\leq 0.75 \cdot R_r$
C	$\leq 0.5 \cdot (R_r + R_s)$	$\leq R_r$
D	$\leq R_s$	$\leq 0.5 \cdot (R_r + R_s)$
E	$\leq 1.5 \cdot R_s$	$\leq R_s$
F	$\leq 2.0 \cdot R_s$	$\leq 1.5 \cdot R_s$
G	$> 2.0 \cdot R_s$	$> 1.5 \cdot R_s$

In the Norwegian scale the class E is supposed to represent the average for the existing stock, while class C is the regulation requirement for new buildings. The class A+ is meant to represent buildings that meet standards that go beyond the class A, as for example the "passive house" standard established by the Passiv Haus Institut in Germany.

It shall be said that the data in Table 5.A1 in Appendix 5.A are given for the Oslo climate. Nevertheless, harmonizing the data on regional distribution of dwellings (Statistics Norway, 2001) with the climatic zones defined by Enova (2006) based on the Degree-Days method, it can be estimated that about 76% of dwellings are located in areas with a climate comparable to or milder than the Oslo climate. Hence, adopting the Oslo climate as an average climate valid for the entire building stock can be considered as a reasonable approximation. The values for R_s and R_r refer to heated floor area, while the data from the GAB register refer to gross floor area. Hence, in order to calibrate the measured intensity data (Intensity = Energy / Activity) with the reference values R_s, it is necessary to use a conversion factor for the reference floor area. The conversion factor is obtained by making the measured intensity equal the R_s intensity. Doing so is comparable to studying an equivalent building stock placed in the Oslo climate, and whose intensities correspond perfectly with the estimations made in the EPBD proposal. The resulting conversion factors from gross to heated floor area are: 0.69 for the residential sector, and 0.80 for the service sector. Figure 5.3 shows the historical development of intensity per heated floor area for both the residential and service sectors. The share of electricity is also shown.

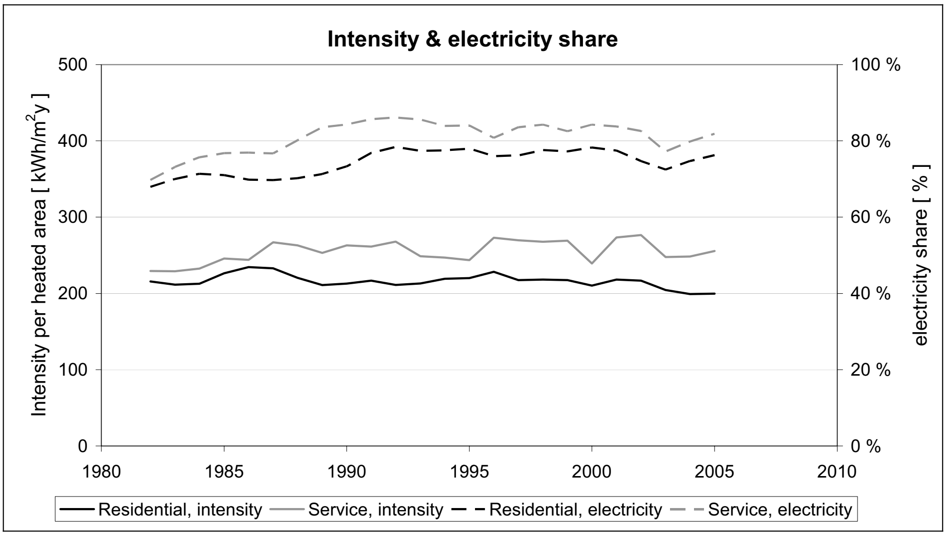

Figure 5.3 **Historical data on intensity and electricity share for the residential and service sectors.**

Concerning the residential sector the intensity seems to have slightly decreased over the last decade. The observed improvement can be linked to two causes. The first and possibly stronger reason is that in recent years, since the beginning of the '90ies, there has been a drop in the construction of single- and double-family houses and row-houses, accompanied by an increased construction of dwellings in blocks of flats (Statistics Norway, 2007b). Apartment dwellings have better energy performances than dwellings in detached houses, see Table 5.A1 in Appendix 5.A. The second cause may be that the stricter regulations in the building code may have gradually had an effect (previous building codes in Norway are from 1987 and 1997). The construction of new buildings that are more and more energy efficient, together with the simultaneous demolition of some old buildings, has resulted in a decrease in the overall average intensity of the stock. Concerning the service sector, the energy intensity does not seem to decrease in the same way as for the residential sector. On the contrary, observations from Enova (2006) would rather suggest that new buildings may consume more than older ones despite the stricter building code's prescriptions. An important part of the reason may be the increased ventilation rates and increased use of glazing in the facades of new buildings compared to older ones.

Finally, it can be seen that R_s values refer to delivered energy because that is the actual measurable quantity. The regulation R_r values, instead, refer to net energy. In the model it is necessary to know both net and delivered energy demand. The relation between net and delivered energy, for each carrier, is given in equation (5.2):

$$E_{net} = E_{delivered} \cdot \eta_{sys} \quad \textbf{(5.2)}$$

where η_{sys} is the overall efficiency (or coefficient of performance, COP) of the technical system. Pettersen et al. (2005) and Wigenstad et al. (2005) present an extensive evaluation of the system efficiencies for typical installations in both the residential and the service sector. This information together, with the analysis on heat pumps by Wachenfeldt and Sartori (2007), provided the overall average efficiencies for each energy carrier reported in Table 5.A2 in Appendix 5.A. The energy carrier efficiencies allow converting net energy into delivered energy and vice versa. In addition, for the existing buildings the net energy demand for electric specific needs and for cooling was assumed to be the same as for new buildings.

5.4 Model

Three hypothetical policies are considered: wide diffusion of thermal carriers, wide diffusion of heat pumps and wide diffusion of conservation measures. When setting the boundary conditions for a scenario it is the intention of the authors to allow for "extreme" situations, so that every scenario will express the maximum potential for a policy. However, limitations are given by contextual constraints, as for example the estimated rates of construction, renovation and demolition. This way the results should quantify the potential and the limits of a strategy. In other words, the results may be interpreted in the following manner: "with the given contextual constraints any policy or action taken in such a direction should not be expected to achieve any better or any faster result than this".

One basic hypothesis made here is that a consistent and enduring change in the net energy demand of a building can be achieved only when a building undergoes major renovation, i.e. extensive works that can change the thermal performance of its envelope. Thus, it is a key feature of the model that a building, or rather a generic square meter, belongs to a certain energy class from the moment it is built until it is eventually renovated. Some minor improvements, like adopting better controls or more efficient lighting or equipment are possible without being part of a major renovation activity. These types of measures are supposedly already incorporated in the best energy classes, so they are implicitly included in new and renovated buildings. Their application could be considered also for the part of the stock that remains unchanged, but the effect should be applied to all scenarios because such measures are independent from the analysed policies. Thus, the final results would be unchanged when comparing the three policies against each other. Therefore, this potential improvement is not considered further.

The share of energy carriers is allowed to change regardless of renovation activity. Where a hydronic heating system is available the shift from one carrier to another can be done easily; when more carriers are available simultaneously the choice between one and another may simply be driven by price fluctuations. On the other hand, if a dwelling or an office does not have a hydronic system it is hard to imagine the installation of pipes and radiators, with consequent discomfort or temporary non-accessibility for the users, if not in the context of a broader renovation project. This may hamper the adoption of thermal carriers. Nevertheless, the observed shift toward thermal carriers in the residential sector is quite limited and it is mainly toward wood, see Table 5.3. A larger shift is observed for the service sector; most buildings in this sector, though, are already equipped with hydronic heating systems (62%). Therefore, it is considered that the expected shift in energy carriers used for heating can take place without the necessity of renovation. This is done in the model by tuning the variable named user preference.

The combination of energy class and user preference form an archetype, as it is described later (see paragraph *Archetypes*). Every generic square meter of floor area in the model is represented by one archetype or another. The model simulation starts with a given existing stock. In addition, three flows of building mass are defined: new construction, demolition and renovation. Each year the new construction flow is assigned to some archetypes (or fractions of the total flow assigned to different archetypes) according to the scenario's hypotheses. The demolition flow simply leaves the stock, so it is removed from the model. The renovation flow re-circulates in the stock, meaning that no square meter is added or subtracted to the model, but there is a portion of the original building mass that "migrates" from some archetypes to others, in accordance with the scenario's assumptions.

To define some boundary conditions for the model, such as the initial user preference or the amount of new construction per year, the authors decided to use as a starting point the historical data over the period from 1996 to 2005, which is the most recent known decade of data. The choice is a compromise between an observation period long enough to avoid bias from yearly fluctuations, but short enough to emphasize emerging solutions, such as district heating and heat pumps. The model is then run for a simulation period that goes from 2006 to 2035. This is a compromise between a time period long enough to let the scenarios develop and depart from the common initial state, but short enough to preserve the validity of the assumptions based on the observation period.

5.4.1 User preference

As mentioned, in the Norwegian building sector electricity is the single most important carrier used for heating purposes. Nevertheless, electricity is often complemented by other carriers, and the actual use of electricity or alternative carriers depends on how the system is run and on price variations. Hence, it is not possible to state directly the user preference for energy carriers by simply looking at the installed heating system.

The user preference expresses the preference given by the users to alternative energy carriers used to satisfy their heating needs. The user preference is derived by combining information on delivered energy, net energy demand and system efficiencies. The values observed in the period 1996-2005 were averaged. The trend observed in the period 1996-2005 is continued linearly until year 2035, and both average and trend values are reported in Table 5.3. For reasons of simplicity also the estimated heat from heat pump is treated like an energy carrier. The term "electricity direct" does not include the electricity for driving heat pumps.

Table 5.3 User preference on carriers for heating.

	year	**Electricity direct**	**District heating**	**Wood**	**Gas**	**Oil**	**Heat from HP**
Residential	Average 1996-2005	80.7 %	0.9 %	8.9 %	0.3 %	8.1 %	1.1 %
	Trend to 2035	61.8 %	2.7 %	18.7 %	2.5 %	0.0 %	14.4 %
Service	Average 1996-2005	71.7 %	6.5 %	0.1 %	0.9 %	15.4 %	5.5 %
	Trend to 2035	31.6 %	29.2 %	1.2 %	7.3 %	3.0 %	27.7 %

Significant changes can be seen between the initial and the final values, especially in the service sector. If the observed trend will continue, direct use of electricity will be more than halved by 2035. District heating and heat from heat pumps will become nearly as important as electricity. The use of gas will also increase, while oil is almost phased off. In the residential sector the direct use of electricity keeps being the most significant carrier, but with a smaller share than in the starting period. The use of wood and heat pumps increase considerably, while gas and district heating keep playing a marginal role. Oil will be completely phased off by 2035.

5.4.2 Archetypes

An archetype is "a statistical composite of the features found within a category of buildings in the stock" (ECBCS, 2004). The structure of an archetype is summarized in Table 5.4. On the left side of the table is the net energy, subdivided into the energy needs: electric, cooling and heating. The electric (specific) need is the sum of electricity demanded for fans and pumps, lighting and other electrical equipment. Cooling means both space cooling and cooling of ventilation air; it is assumed that cooling is provided by electricity-driven systems. The heating need is the sum of space-, ventilation- and tap water heating. The total net energy demand is uniquely determined by the building's energy class. On the right end side of the table is the delivered energy, subdivided into the energy carriers. The free heat from heat pumps is reported in brackets because it is not an actual carrier, and it is not included in the total of delivered energy. The figures for delivered energy are obtained by the net energy considering the user preference, see Table 5.3, and the carrier efficiencies, see Table 5.A2 in Appendix 5.A. As the carrier efficiencies are fixed in the model, the delivered energy becomes a function of the energy class and the user preference. An archetype is then completely defined by a combination of an energy class and a user preference, where both are chosen according to the scenario's hypotheses.

Table 5.4 The archetype's structure.

Archetype *XY*: Energy class *X*, User preference *Y*				
Net energy			**Delivered energy**	
energy need	[kWh/m^{2}y]		energy carrier	[kWh/m^{2}y]
total Net			**total Delivered**	
electric	*x1*		electricity	*y1*
cooling	*x2*	*"➔ user preference*	district heating	*y2*
heating	*x3*	*and*	wood	*y3*
		carrier efficiencies ➔"	gas	*y4*
			oil	*y5*
			(free heat HP)	*(y0)*
Energy class dependent			*User preference dependent*	

A closer look at the details of such calculations is given in Appendix 5.B. The archetypes shown are representative of stock and regulation references, R_s and R_r, when adopting the observed average user preference, see Table 5.3. The archetypes describing R_s and R_r represent the energy classes E and C respectively. Archetypes were created for all other user preference options: the two trend values reported in Table 5.3 plus two other alternatives specified by the scenarios. Combining four user preferences with six energy classes (from A+ to E) and two sectors adds up to a total of 48 archetypes. A further level of detailing may include subdivisions based on climatic zones, type of area (urban/rural, high/low energy density), disaggregation of building sectors into categories, age groups and types of heating system available. Apart from the difficulties in resourcing the necessary information – unfortunately often scarce or inexistent – the number of archetypes would grow rapidly, and the potential benefit coming from a more detailed description of the stock should be weighted against the increasing complexity of the model.

5.5 Scenarios

The scenario analysis is performed for the purpose of investigating the quantitative potential of three hypothetical policies in reducing total energy and electricity demand in the Norwegian building stock. The three policies are: wide diffusion of thermal carriers, wide diffusion of heat pumps and wide diffusion of conservation measures. The differences between the scenarios are obtained implementing different options for the new construction and renovation flows. The scenarios are ultimately defined by a combination of energy class and user preference hypotheses. Energy class and user preference can be seen as the two driving forces that make the model develop in one direction or another. More precisely the first two policies, thermal carriers and heat pumps diffusion, act on the user preference while the latter one, diffusion of conservation measures, acts on the energy class. The energy class and the user preference are two independent characteristics of an archetype; therefore it is also possible to combine the energy conservation policy with the two others to form additional scenarios. The scenarios analysed in this work are the following:

- ***Base***: reference scenario, based on observed trends and with no implementation of any specific policy.
- ***Thermal***: scenario implementing the policy for maximum diffusion of thermal carriers.
- ***Heat Pump***: scenario implementing the policy for maximum diffusion of heat pumps.
- + ***Conservation***: implementation of the policy for maximum diffusion of energy conservation measures, adopted in addition to the other hypotheses in all three previous scenarios.

The hypotheses on energy class and user preference are specific for each scenario; these hypotheses determine the Intensity matrix. Common assumptions are set regarding the flows of new, demolished and renovated square meters in order to define an Activity matrix that is common to all scenarios. These hypotheses are presented first.

5.5.1 Hypotheses on Activity

The basic hypotheses about the activity levels are presented in Table 5.5, where all data are presented in gross floor area. Data on stock and new construction are taken from the GAB register. The stock increase in both residential and service sectors appears to be nearly linear, see Figure 5.2. This is in line with the population increase for the same period, which also has been nearly linear (Statistics Norway, 2007c). The same statistics projects the expected increase in Norwegian population in the next decades to continue with approximately the same pace. Hence, the stock is also expected to continue its linear growth, and the flow of new construction is set equal to that of the observed period. It can be seen that the average construction activity between 1996 and 2005 corresponds to about 1.0% and 1.4% of the 2005 reference stock, in the residential and service sectors respectively. This indicates that there has been a relatively higher activity in the service sector.

Regarding demolition and renovation, data had to be inferred from other sources, and the scarce information available was mainly for residential buildings. According to Myhre (2000) and Rødseth et al. (1997) a reasonable estimate would be to assume that 5,000 dwellings are demolished every year. With an average size of dwellings of about 130 m^2, as from GAB database, this results in 650,000 m^2/y of demolition activity. This demolition rate corresponds approximately to 0.2% of the residential reference stock of year 2005. Concerning renovation, for the Norwegian dwelling sector Rønningen (2000) shows that in year 1998 the renovation activity corresponded to about 77 % of new construction; he says this may be an underestimate. From Statistics Norway (2006) it emerges that in the period between 1971 and 2001 50% of the building stock has been renovated. Caution should be used in reading these data because it is not clear how the respondents might have interpreted the query about “major work that has been carried out to raise the standard of the dwelling”. It is probable that in most cases respondents referred to renovation of parts of the dwelling; e.g. replacing windows or heating system, re-doing the roof or simply renewing the kitchen or bathroom (which would not have significant impact on energy performance). Nevertheless, 50% of the stock renovated in 30 years means a median value of 30 years for the renovation interval. In their work Sartori et al. (2008) assumed an interval of 40 years as representative of major renovations that could allow for altering the building's energy performance. Their outcome is that in the period between 1971 and 2001 only 19% of the stock was renovated – i.e. significantly lower than statistics records – but they also show that renovation may overtake construction around 2010 and be the principal activity for the coming decades. However, due to the high uncertainty of the estimates and following a precautionary principle, the renovation activity in the model is not considered to become predominant, but it is set equal to the construction activity throughout the simulation period.

Table 5.5 Hypotheses on Activity, common to all scenarios.

	Residential sector		**Service sector**	
	[m^2/year]	Notes	[m^2/year]	Notes
Observed data, 1996-2005				
New	≅ 3 280 000	GAB register, average	≅ 1 740 000	GAB register, average
Demolition	≅ 650 000	0.2% of 2005's stock		
Renovation	≅ 5 000 000	from Statistics Norway (2006)		
Model data, 2006-2035				
New	= 3 280 000	to continue the trend	= 1 740 000	to continue the trend
Demolition	= 650 000	to continue the trend	= 500 000	0.4% of 2005's stock
Renovation	= 3 280 000	as new; lower than observation	= 1 740 000	as new

For the service sector, as for the residential one, the renovation flow was set equal to the new construction because no better data were found in literature. The demolition rate is set to 0.4% of the 2005 reference stock, which is the double of that for the residential sector. This assumption reflects the fact that non-residential buildings usually have a shorter lifetime than residential buildings.

The assumptions summarised in Table 5.5 lead to the following conclusions: in the residential sector, 6% of the reference 2005 stock will be demolished by 2035 and 63% will remain unchanged. This means that the final stock in 2035 will be composed of 51% of unchanged buildings, 24.5% renovated and 24.5% new construction. In the service sector, 12% of the reference 2005 stock will be demolished by 2035 and 47% will remain unchanged. This means that the final stock in 2035 will be composed of 36% of unchanged buildings, 32% renovated and 32% new construction. Note that double renovation of the same buildings not is allowed in the model.

5.5.2 Hypotheses on Energy class

Some of the hypotheses on energy class are common to all scenarios, others are scenario specific. Where not otherwise specified, the hypotheses hold true for both the residential and service sectors. They are summarised as follows:

- The reference stock in year 2005 is in class E since this is the class that is supposed to represent the average for the stock. It may be argued that representing the entire stock with a single energy class is a coarse approximation and more age groups should be used. On the other hand, as many buildings have been renovated (50% only in the period 1971-2001), it would be misleading to make a categorisation strictly based on "as built" characteristics. The buildings that are demolished yearly are also supposed to be in class E on the average, so that the energy class of the remaining stock is not altered. Renovation in year 2005 simply restores the energy class E. New construction in year 2005 is in class D for the residential sector and in class E for the service sector, as a consequence of the observations made in the paragraph *Intensity*.

- ***Base***: the above behaviour is continued until 2035.
- \+ ***Conservation***: all scenarios start from the basis of the EPBD as the initial state. The directive starts producing its effects in 2010 with new construction in class C and renovation achieving class D. Then, a transition period is set for new construction from 2010 to 2015, and for renovation from 2010 to 2020. At the end of the transition period all new buildings have class A+ and all renovated ones reach energy class A. This is called the final state. The transition period is needed to simulate the time required for extensive diffusion of certain design concepts, materials, technologies and practical expertise. During the transition period the new and renovation flows migrate gradually from the initial to the final archetypes. The transition period is assumed longer for the renovation flow to allow for new materials and technologies as well as for practitioner experience to be developed in new construction and then gradually adopted also in renovation. This is because technical difficulties and costs are generally higher in renovation than in new construction. For the same reason also the final state is not the same.

5.5.3 Hypotheses on User preference

Some of the hypotheses on user preference are common to all scenarios, others are scenario specific. Where not otherwise specified, the hypotheses hold true for both the residential and service sectors. They are summarised as follows:

- The original stock in year 2005 has the user preference reported in Table 5.3, and the unchanged stock follows the trend from the same table until 2035. In all scenarios until year 2010 also new and renovated buildings follow the same trend as the stock.
- ***Base***: the above behaviour is continued until 2035.
- In both the Thermal and Heat Pump scenarios a transition period is implemented, similarly to what is described above for the energy class in the scenarios with conservation measures. During the transition period there is a smooth change from the initial to the final state. The initial state is the same as for the Base scenario; the final state is described below for each scenario. The transition period is meant to represent some inertia to change in the energy system. This can be due either to the necessity to set up an infrastructure, as for district heating or gas, or simply to the fact that new habits take time to make their way into society.
- ***Thermal***: all new and renovated buildings in the final state will have a user preference of 25% for direct electricity; the remaining 75% of the heating need being covered by thermal carriers. The choice of keeping a quarter of direct electricity use even in a scenario for thermal carriers is due to the fact that not all locations can be covered by gas or district heating networks. Besides, electric heating can be combined with wood stoves when hydronic systems are not installed. Also, direct electric heating is a flexible and efficient solution for spaces that need to be heated intermittently, because of its small thermal inertia.

Regarding the 75% from thermal carriers, no hypothesis is made on whether gas, wood or district heating is used. As the main goal is to study the substitution of electricity with thermal carriers in general, it is not critical what the actual contribution of each single thermal carrier is. Concerning the efficiency, an average between gas, wood and district heating efficiencies is taken. Oil is, however, completely phased off.

- ***Heat Pump***: all new and renovated buildings in the final state will have a user preference as follows. In the service sector heat pumps will cover 75% of the heating need and direct electricity only 25%. In the residential sector heat pumps will cover 50% of the heating need while direct electricity covers the other 50%. In residential units the demand for hot water is more significant than in non-residential buildings. It was assumed (see paragraph on *Energy*) that heat pumps installed in residential buildings are air-to-air heat pumps. This implies that they cannot be used to cover the domestic hot water demand. Besides, some rooms may require higher comfort levels that are difficult to achieve by heat pumps, i.e. bathrooms in Norway are typically equipped with electrical floor heating for comfort reasons.

5.6 Results and discussion

This section presents, analyses and compares the results for the different scenarios. An overall view is given in Figure 5.4 where the past and the projected delivered energy demand is represented. The figures refer to the entire building stock, i.e. both the residential and service sectors together.

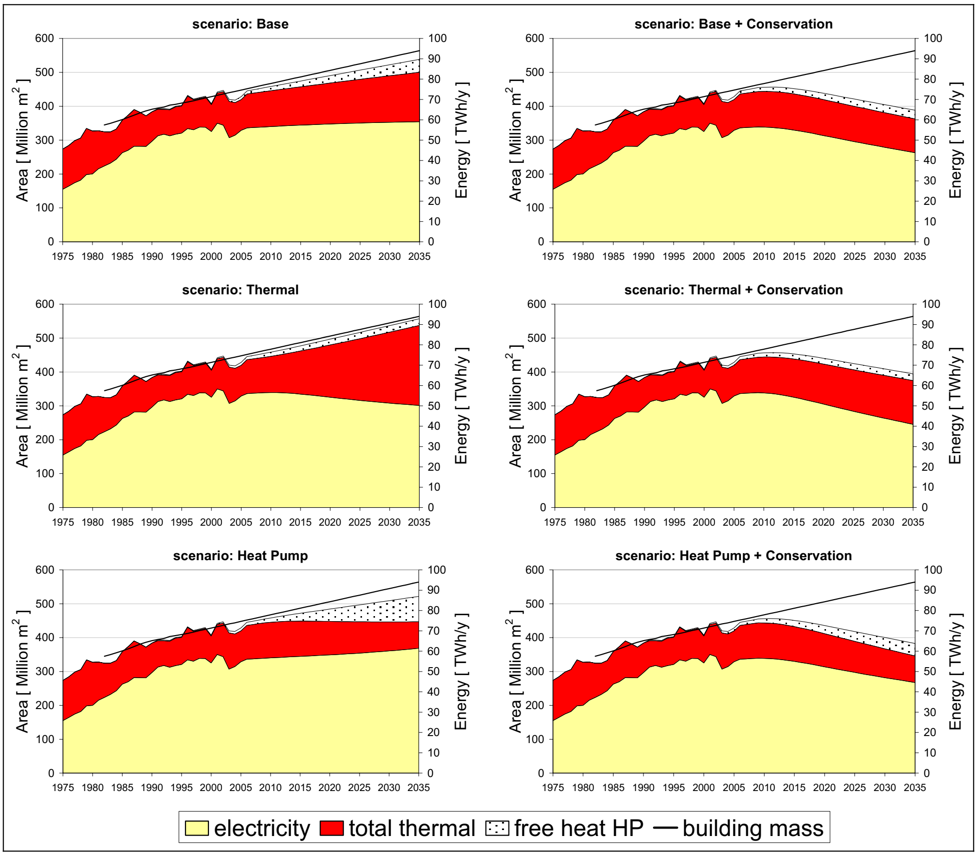

Figure 5.4 **Delivered energy results for the different scenarios. On the left side: *a)* Base, *b)* Thermal and *c)* Heat Pump. On the right side the same scenarios plus energy conservation measures: *d)*, *e)* and *f)* respectively.**

5.6.1 Policy aspects

There is a clear difference between the left and the right hand side of Figure 5.4. This is a result of the fact that the scenarios on the right hand side include energy conservation. The right hand graphs show reduction in both electricity and total delivered energy compared with the corresponding left hand graphs. This outcome is a direct consequence of the hypotheses about energy class and underlines the fact that in theory there is no contradiction between conservation measures and other technologies. This also means that a policy for energy conservation measures is a robust policy because it can guarantee, within a certain margin, the achievement of target results even under conditions of wide uncertainty in the user preferences. Indeed, the two scenarios Thermal and Heat Pump represent two extreme and opposite cases of how the user preferences may develop, and in both cases the adoption of conservation measures lead to similar results.

On the other hand, it may be argued that the effect of the other policies is dampened by the adoption of conservation measures, creating a *de facto* contradiction between the policies. For example – as analysed in detail by Thyholt (2006) – on the supply side the profitability of developing a district heating network would be reduced when the overall demand of a given area is reduced. Infrastructures for district heating or gas are more profitable in areas with higher energy density. Therefore, large investments in the expansion of such infrastructures would conflict with investments in energy efficiency. Nevertheless, the problem of "permanent lock-in" (as described by Nässen, 2005) where the choice between supply and demand strategies always would favour substitution of fuels at the expense of energy efficiency should be avoided. To overcome this risk, the building stock should rather be seen as an energy infrastructure itself, and energy policies should aim at maximising its efficiency.

A summary of the model's results for every scenario is given in Table 5.6. The data are presented for type of carrier, whether electricity or the sum of all thermal carriers, for sector, whether residential or service, and for building status, whether unchanged stock, renovation or new construction.

Table 5.6 Delivered energy for all the scenarios. Totals and grouped by different criteria.

Delivered Energy by year 2035 [TWh/y]								
Scenario	Total	Electricity	Thermal carriers	Residential	Service	Stock unchanged	Renovation	New
Reference year 2005	72	56	16	46	26			
Base	83	59	24	51	32	39	23	21
Thermal	90	50	39	54	35	39	27	24
Heat Pump	74	61	13	46	28	39	18	17
Base + Cons.	60	44	17	39	22	39	12	9
Thermal + Cons.	62	41	22	40	23	39	13	10
Heat Pump + Cons.	58	45	13	37	20	39	10	8

Figure 5.5 compares the results for all scenarios as in year 2035; the situation in the reference year 2005 is also reported for comparison[4]. The total is divided into electricity and the sum of thermal carries. The percentage reported inside the grey bars is the percentage of electricity share. The dashed line represents the electricity demand for the reference year 2005.

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[4] the reference year 2005 has the actual stock of year 2005 but energy class and user preference defined as the trend value of the observation period 1996-2005.

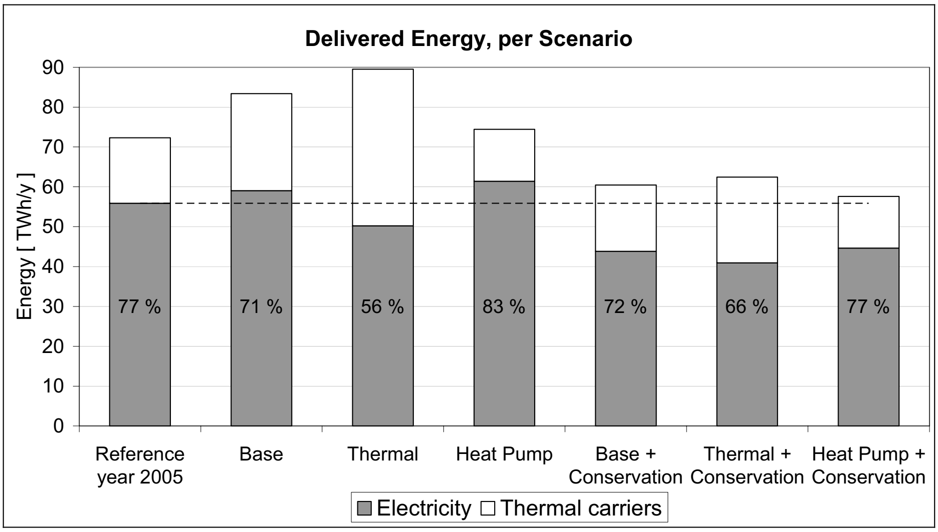

Figure 5.5 **Total delivered energy by 2035 for each scenario, divided into electricity and sum of thermal carriers.**

With respect to the reference year 2005 the Base scenario presents an increase in total energy demand in year 2035 of about 11 TWh/y, divided in: +3 TWh/y in electricity demand and +8 TWh/y in thermal carriers. In the Thermal scenario the total demand is the highest of all, about 18 TWh/y higher than 2005's value, as the result of two opposite trends: electricity demand -6 TWh/y and thermal carriers demand +23 TWh/y. Altogether, the share of electricity goes as far down as 56%, the lowest value. Hence, the dependency on electricity is reduced both in relative and in absolute terms with respect to the year 2005, but this achievement has to be paid by a significant increase in the use of thermal carriers. The exact opposite situation is observed for the Heat Pump scenario. Here the total increase is contained to 2 TWh/y, again as the combination of two diverging trends: +5 TWh/y electricity and -3 TWh/y thermal carriers demand. The share of electricity is 83%, the highest value for all scenarios. The electricity dependency has grown both in percentage and absolute value from year 2005, but the overall demand growth is the smallest amongst the scenarios without conservation measures.

Hence, both the Thermal and the Heat Pump scenarios seem to have both a positive and a negative outcome. On one hand it is possible to reduce electricity dependency at the price of higher total consumption; on the other hand it is possible to limit the total consumption at the price of increasing electricity dependency. This creates a conflict in the outcome that makes it difficult to evaluate the overall goodness of the policies. In the case that a shift toward thermal carriers or the adoption of heat pumps would take place also in the unchanged stock, these conflicting effects would even be accelerated and amplified.

The situation becomes clearer when the policy for conservation measures is introduced. The differences between the three scenarios with conservation are notably smaller. In all of these the electricity demand is lower than in 2005, with a consistent reduction that varies between -11 and -15 TWh/y. The degree of electricity dependency is also smaller than in 2005 for all three scenarios. The effect on thermal carriers varies between -3 and +6 TWh/y from the 2005 reference, but does never counterbalance the positive achievements in electricity demand reduction.

It may be argued that the total savings (10-14 TWh/y) are relatively small because they lie in the range of 14-20% compared with the reference year 2005. It shall not be forgotten that these savings take place while the building stock increases, as illustrated in Figure 5.4 where the total energy curve is shown together with the building mass curve. In the historical records the growth in building mass is closely accompanied by an equivalent increase in energy demand. This behaviour is expected to continue unless conservation measures are adopted. In that case a reverse trend can be expected, and both electricity and total energy demand will decrease, slowly but steadily, even though the stock keeps on growing. In 2035 the building stock in the model will be some 116 million m^2 more than in 2005, i.e. about 26% more. While the building stock grows 26% larger, the energy demand is expected to become 14-20% smaller.
Figure 5.6 shows the results grouped by renovation, grey bars, and new construction, white bars. Differences in total energy consumption compared to the Base scenario are shown.

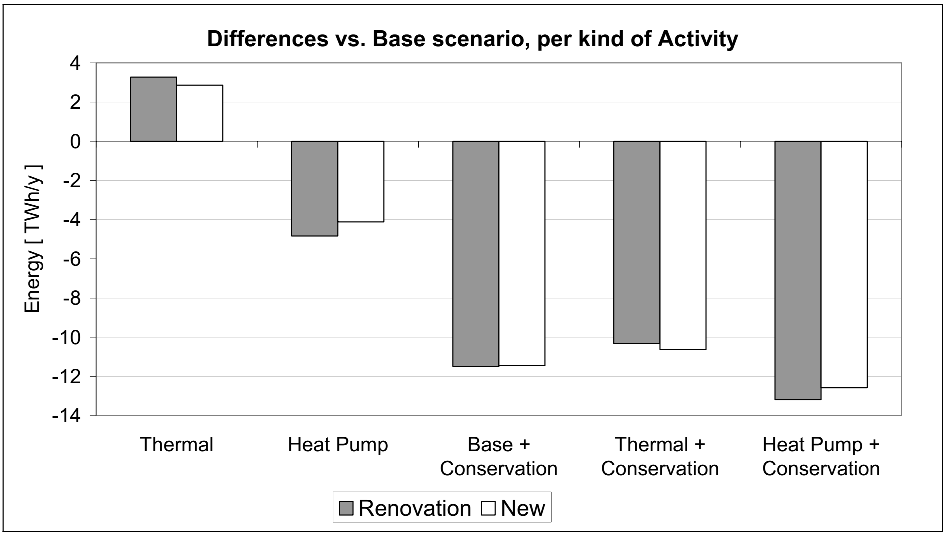

Figure 5.6 **Differences in energy consumption vs. Base scenario by 2035, divided into renovation and new construction activities.**

Compared with the Base scenario, the total savings from scenarios with conservation varies between 21 and 25 TWh/y. The savings from the Heat Pump scenarios are less than half, while the Thermal scenario is the only one that increases the energy demand with respect to the Base scenario. It is interesting to notice the differences between the new and renovation activities. In the model the level of activity was set equal for both new construction and renovation (see paragraph *Hypotheses on Activity*) and so the differences seen in Figure 5.6 are due to the hypotheses on intensities. In the scenarios without conservation the energy class never differs from the initial conditions. This means that in the residential sector – where new construction is in class D and renovation is in class E – any shift in the user preference has a greater impact on renovation than on new construction. When introducing conservation measures, instead, the final target for new construction becomes the class A+ while renovation achieves class A; the difference between the two classes is not as pronounced as between classes E and D. In addition, the transition period is shorter for the new activity's flow. Altogether, these settings are responsible for the outcome visible in Figure 5.6, where the renovation and new activities have nearly the same importance. Had better guesses been available on the rate of renovation the results would have looked different.

5.6.2 Methodology aspects

Regarding the behaviour of the model, Figure 5.4 illustrates the inertia that characterises all scenarios. Even though the assumptions behind the scenarios are supposed to be extreme, the contextual constraints on how changes can happen prevent the model from changing too fast. This aspect marks a major difference from other works, where the inertia of the building stock appears not to be captured.

The results for the residential sector can be compared with those from Myhre (2000); the numbers are summarised in Table 5.7. The initial conditions are somewhat different. Myhre's estimate on stock consumption is higher than what is estimated in this work in the starting year, when his stock is smaller. This difference is merely due to different estimations; no actual (significant) energy efficiency improvement has occurred between 1998 and 2005. Furthermore, Myhre assumes the stock to increase 38% in 32 years, while here it is assumed to increase 26% in 30 years. Therefore, it is natural that Myhre will estimate an even higher consumption when his stock grows larger, in the final year. Considering the differences in stock size and initial conditions, the results from the two works seem to be in relatively good accordance for the total consumption in the reference scenarios. On the other hand, dependency on electricity is considerably higher in Myhre's reference scenario because he makes the hypothesis that all new construction use only electricity for heating. In the best performing scenarios, however, the improvements are stronger in Myhre's work than in this work. This is due to assumptions on renovation activity. In Myhre's work the portion of stock that remains unimproved after 32 years is assumed being 50% in the reference scenario, but in the high energy efficiency scenario the entire stock is converted to high standards of energy efficiency.

This means that Myhre assumes different levels of renovation activity in his scenarios. In this work, on the other hand, the portion of unchanged stock is 63% in all scenarios. The authors assume the renovation activity being constant in all scenarios; whether or not a building is to be renovated is something that goes beyond considerations of energy efficiency. The policy for introducing conservation measures simply exploits the renovation as a moment for introducing energy efficient solutions. The possibility that a policy on energy efficiency would be able to stimulate renovation activity is not considered.

Table 5.7 Comparison with Myhre (2000).

		Stock[a] [Million m^2]	Total energy [TWh/y]	Electricity [TWh/y]	Original stock unchanged
	starting year				
Myhre (2000)	1998	211	49	35	100%
This work	2005	220	46	35	100%
	final year				
Myhre (2000), reference	2030	291	60	47	50%
This work, Base	2035	274	51	37	63%
	final year				
Myhre (2000), high energy efficiency	2030	291	36	29	0%
This work, Base+Conservation	2035	274	39	29	63%

[a] heated floor area

In their work Johansson et al. (2006 and 2007) make scenarios for the Swedish building stock, so the results are not comparable with those of this work; but it is worth comparing some of the assumptions. Their study has a major focus on the supply side and so they do not investigate thoroughly the possible variation in energy demand. Rather, they make assumptions about it. One of their scenarios assumes a 30% decrease in heat demand in the existing stock. The measures taken to achieve such improvement are said to be economically competitive measures that include: replacement of windows, additional insulation, new ventilation systems with heat recovery and replacing of heating system. These estimates on the intensity level appear absolutely reasonable. The problem is that the entire stock is assumed to undergo such changes in intensity level in just 22 years, from 2003 to 2025 (the simulated period). Because the demolition activity assumed is negligible (0.03% annually) that would imply that 4.5% of the stock have to be renovated every year. Equivalently, adopting the assumption of this work that part of the stock remains unchanged while part is renovated to a high standard of energy efficiency (class A) leads to the conclusion that 40% of the stock is renovated in 22 years. Annualizing, that becomes a renovation rate of 1.8% per year, which is six times higher than the declared construction rate of 0.3% per year. This may well be the case in the Swedish building stock. Nevertheless, it is important to state explicitly both intensity and activity levels and distinguish clearly what is part of the common assumptions and what is scenario specific.

5.7 Conclusions

The evaluation of the three hypothetical policies outlines the robustness of a policy on conservation measures against the conflicting effects of the other polices on thermal carriers and heat pumps. Adopting conservation measures on a large scale does allow reducing both electricity and total energy demand from present day levels while the building stock keeps growing.

Regarding the methodology, a model has been developed based on the notions of archetypes and activity flows. The most important feature revealed by such a model is the inertia to change of the building sector, observed in all scenarios. This represents perhaps the major difference from other works. In this model the activities of construction, demolition and renovation are explicitly defined and are independent from the scenario analysis. Especially, the renovation activity is defined a priori and is not a function of a specific scenario or policy. The situation is different in other works, where improvements in the existing stock are applied, either explicitly or implicitly, to different portions of the stock in different scenarios. This has major consequences for the results. Whether or not the amount of renovation activity may be affected by a policy is questionable. For example, economic incentives to achieve a class A level of energy efficiency in a renovation project may be attractive for those who have already planned a renovation. However, such incentives would not necessarily attract people doing renovation works if that was not already in their plans. At least, the hypotheses on activity and intensity levels should be kept separated and analysed separately.

Further work would be necessary to consider aspects like: climatic zones, type of area (urban/rural, high/low energy density), disaggregation of building sectors into categories, age groups and type of heating systems available. Extending the boundaries of the model is also necessary for allowing estimation of CO_2 emissions. As an alternative, a detailed analysis of the energy demand side could be used to provide input to models for the analysis of the supply side. Supply side models usually assume energy demand as an exogenous variable; estimations made on the basis of demand side models like the one presented here would provide better guesses than a simple trend analysis of past values.

5.8 Acknowledgments

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Appendix 5.A

Table 5.A1 Intensity values for several types of building.

Gab code	Type of building	Rs, delivered energy [kWh/m^{2}y]	Rr, net energy [kWh/m^{2}y][a]									Share of building mass in 2005
			Total	Heating	Ventilation	Hot water[b]	Fans and pumps[b]	Lighting	Equipment	Room cooling	Ventilation cooling	
11x, 12x, 13x	Small house	229	129	45	6	30 (37)	8 (1)	17	23	0	0	80 %
14x, 15x	Apartments block	218	118	31	7	30 (40)	10 (1)	17	23	0	0	12 %
16x	Holiday house	47	47									8 %
31x, 39x	Office	233	165	34	21	5	22	25	34	0	24	23 %
32x, 33x	Shop	390	237	44	34	10	42	56	4	0	47	16 %
4xx	Transport & comm.	246										5 %
5xx	Hotel & restaurant	296	239	61	29	30	35	47	6	0	31	7 %
61x	School	194	137	40	27	10	25	22	13	0	0	13 %
62x, 63x	University		179	34	24	5	27	25	34	0	30	2 %
612	Kinder garden	224	152	67	26	10	23	21	5	0	0	0 %
65x	Sport	279	185	48	40	50	23	21	3	0	0	4 %
64x, 66x, 67x, 69x	Culture	188	178	66	26	10	24	23	3	0	26	8 %
71x	Hospital	390	327	57	42	30	54	47	47	0	50	2 %
72x, 73x, 79x	Nursery	279	234	48	38	30	48	47	23	0	0	5 %
8xx	Prison etc.	249										2 %
9xx	Other											13 %

[a] End use values are indicative estimations.

[b] Values referring to the existing stock (Rs, delivered energy), when they are known, are reported in parentheses.

Table 5.A2 **Efficiency or COP associated with energy carriers.**

	electric needs	**cooling needs**	**heating needs**					
	electricity	electricity	oil	gas	wood	district heating	electricity	heat from HP
Residential	1.00	2.40	0.77	0.81 – 0.86[a]	0.4 – 0.6[a]	0.88	1.00	2.16
Service	1.00	2.40	0.77	0.86	0.70	0.88	1.00	2.32

[a] Left value in existing stock, right value in new and renovated.

Appendix 5.B

Table 5.B1 **Archetype for residential sector, stock reference Rs.**

class E, Rs net energy						**delivered energy**					
energy need	kWh/m^{2}y	share	carrier	user preference	kWh/m^{2}y	efficiency or COP	carrier	kWh/m^{2}y	energy carrier	kWh/m^{2}y	share
	190.0									212.8	
electric	**41.0**	21.6 %				1.00	electricity	41.0	electricity	162.0	76.1 %
cooling	**0.0**	0.0 %				2.40	electricity	0.0			
heating	**149.0**	78.4 %	electricity direct	80.7 %	120.2	1.00	electricity direct	120.2			
			district heating	0.9 %	1.4	0.88	district heating	1.6	district heating	1.6	0.7 %
			wood	8.9 %	13.2	0.40	wood	33.0	wood	33.0	15.5 %
			gas	0.3 %	0.5	0.81	gas	0.6	gas	0.6	0.3 %
			oil	8.1 %	12.1	0.77	oil	15.7	oil	15.7	7.4 %
			heat from HP	1.1 %	1.7	2.16	ele. to drive HP	0.8			
							free heat HP	0.9	free heat HP	0.9	---

Table 5.B2 **Archetype for residential sector, regulation reference Rr.**

class C, Rr net energy						**delivered energy**					
energy need	kWh/m^{2}y	share	carrier	user preference	kWh/m^{2}y	efficiency or COP	carrier	kWh/m^{2}y	energy carrier	kWh/m^{2}y	share
	121.0									132.2	
electric	**48.0**	39.7 %				1.00	electricity	48.0	electricity	107.3	81.1 %
cooling	**0.0**	0.0 %				2.40	electricity	0.0			
heating	**73.0**	60.3 %	electricity direct	80.7 %	58.9	1.00	electricity direct	58.9			
			district heating	0.9 %	0.7	0.88	district heating	0.8	district heating	0.8	0.6 %
			wood	8.9 %	6.5	0.40	wood	16.2	wood	16.2	12.2 %
			gas	0.3 %	0.2	0.81	gas	0.3	gas	0.3	0.2 %
			oil	8.1 %	5.9	0.77	oil	7.7	oil	7.7	5.8 %
			heat from HP	1.1 %	0.8	2.16	ele. to drive HP	0.4			
							free heat HP	0.4	free heat HP	0.4	---

Table 5.B3 **Archetype for service sector, stock reference Rs.**

class E, Rs **net energy**						**delivered energy**					
energy need	kWh/m^{2}y	share	carrier	user preference	kWh/m^{2}y	efficiency or COP	carrier	kWh/m^{2}y	energy carrier	kWh/m^{2}y	share
	272.0									262.2	
electric	**82.0**	30.1 %				1.00	electricity	82.0	electricity	215.0	82.0 %
cooling	**24.0**	8.8 %				2.40	electricity	10.0			
heating	**166.0**	61.0 %	electricity direct	71.7 %	119.0	1.00	electricity direct	119.0			
			district heating	6.5 %	10.7	0.88	district heating	12.2	district heating	12.2	4.7 %
			wood	0.1 %	0.1	0.70	wood	0.2	wood	0.2	0.1 %
			gas	0.9 %	1.5	0.86	Gas	1.7	gas	1.7	0.7 %
			oil	15.4 %	25.5	0.77	Oil	33.1	oil	33.1	12.6 %
			heat from HP	5.5 %	9.1	2.32	ele. to drive HP	3.9			
							free heat HP	5.2	free heat HP	5.2	---

Table 5.B4 **Archetype for service sector, regulation reference Rr.**

class C, Rr **net energy**						**delivered energy**					
energy need	kWh/m^{2}y	share	carrier	user preference	kWh/m^{2}y	efficiency or COP	carrier	kWh/m^{2}y	energy carrier	kWh/m^{2}y	share
	192.0									180.2	
electric	**82.0**	42.7 %				1.00	electricity	82.0	electricity	155.7	86.4 %
cooling	**24.0**	12.5 %				2.40	electricity	10.0			
heating	**86.0**	44.8 %	electricity direct	71.7 %	61.7	1.00	electricity direct	61.7			
			district heating	6.5 %	5.6	0.88	district heating	6.3	district heating	6.3	3.5 %
			wood	0.1 %	0.1	0.70	wood	0.1	wood	0.1	0.1 %
			gas	0.9 %	0.8	0.86	Gas	0.9	gas	0.9	0.5 %
			oil	15.4 %	13.2	0.77	Oil	17.2	oil	17.2	9.5 %
			heat from HP	5.5 %	4.7	2.32	ele. to drive HP	2.0			
							free heat HP	2.7	free heat HP	2.7	---

Toward modelling of construction, renovation and demolition activities: Norway's dwelling stock 1900-2100

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6 Toward modelling of construction, renovation and demolition activities: Norway's dwelling stock 1900-2100

6.1 Abstract

The activities of construction, renovation and demolition related to the dwelling stock have strong impact on both material and energy demands. A deeper understanding of the dynamics driving these activities is a precondition for a more consistent way to address material and energy demands. The method presented here is based on a dynamic material flow analysis and is applied to the Norwegian dwelling stock. Input data to the model are population and socio-economic lifestyle indicators such as average number of persons per dwelling and average size of dwellings; these determine the size of the floor area stock. Parameters such as lifetime of dwellings and renovation intervals complete the input set. Outputs of the model are the stock and flows of floor area for the period from 1900 to 2100. Analysis of the renovation activity is given particular attention. Several scenarios are considered in order to test the model sensitivity to input's uncertainties. Results are compared with statistical data, where the latter are available. The main conclusion is that in the coming decades renovation is likely to overtake construction as the major activity in the Norwegian residential sector.

6.2 Introduction

Up to today in many countries the population's need for housing has created a large standing stock of residential buildings, also named the dwelling stock. Associated with a dwelling stock there is considerable activity of construction, demolition and renovation (C&D activities), and a corresponding impact on material use, energy use and waste generation. Despite the importance of the dwelling stock and related C&D activities, the understanding of the dynamics and long term changes in the dwelling system is limited. Projections of waste generation and materials demand from building systems are often performed on the basis of trend analysis (Kohler and Hassler, 2002; Kohler and Yang, 2007). The same applies to the analysis of energy demand in buildings (Johansson *et al.* 2006, 2007; Myhre, 1995; Myhre, 2000). Applying a simple trend analysis might represent a sufficiently good approximation if limited to a short period of time, such as the recent past or the immediate future. However, it may fail to grasp the long term effects. In order to improve the understanding of the dwelling stock dynamics, several authors call for, or make use of, dynamic modelling (Bergsdal *et al.*, 2007a; Bergsdal *et al.*, 2007b; Bradley and Kohler, 2007; Johnstone, 2001a, b; Kohler and Hassler, 2002; Müller *et al.*, 2004; Müller, 2006). A dynamic analysis takes into consideration the activity levels of the past and their interrelations and attempts to explore how these will affect the future activity levels.

Construction and demolition are the two activities usually receiving the most attention. However, several studies indicate that renovation has become or will become the dominating activity related to the built environment; measured either in terms of economic investments or in floor area. Rønningen (2000) reports renovation activity to 77% of construction activity in Norway in 1998, while Kohler and Hassler (2002) argue that refurbishment will overtake new construction as the dominant construction activity in Germany in the years ahead. Similar results are found for Switzerland by Kytzia (2003), where expenditures for usage, maintenance and upgrading of buildings are reported to exceed expenditures for new construction. Caccavelli and Genre (2000) estimate that more than one third of total construction's economic output in the European Union is related to refurbishment activities, and that this figure is expected to grow as the housing stock becomes older. The ageing of the housing stock is a fact observed by several authors. According to Itard and Klunder (2007), the majority of the housing stock in the EU was constructed after the Second World War. The same result is found for the Norwegian housing stock in Bergsdal *et al.* (2007b). Martinaitis *et al.* (2007) reports a significant portion of the building stock in Central and Eastern Europe being constructed between the 1960s and the 1990s.

The main purpose of this article is therefore to propose a methodology for analyzing and forecasting the full range of C&D activities in a consistent manner, including renovation.

The modelling approach is based on a dynamic material flow analysis (MFA) initially proposed by Müller (2006) who applied it to the dwelling stock in the Netherlands. He estimated the floor area stock and flows of construction and demolition, as well as the corresponding stock and flows of concrete in the period 1900 to 2100. The same model was adopted and modified in Bergsdal *et al.* (2007b) and applied to the Norwegian dwelling stock for the same period of time. Modifications were made to introduce a simplified approach to the renovation activity, only linked to material's turnover. The corresponding stock, waste generation and material demand for concrete and wood were also estimated. The work presented here is also based on data for the Norwegian dwelling stock. The renovation flow(s) in this paper is treated in a more consistent way, linking it directly to the floor area turnover. Hence, all the C&D activity levels are measured in physical units as square meters of floor area per year. The method is intended to serve as a basis for future analysis of materials demand and waste generation, as well as analysis of energy demand and opportunities for energy performance improvement. Both material and energy figures can, indeed, be expressed as intensities per square meter. Past and future activity levels and the influence and importance of the modelling inputs are discussed on the basis of scenario evaluations. The results are compared against statistical figures where such information is available.

6.3 Method

The conceptual outline of the model is given in Figure 6.1. Processes and stocks are represented by rectangles, flows by ovals, and drivers and parameters by hexagons; solid lines show connections between stock and flows while dashed lines represent influences of the drivers and parameters. Stocks of population and floor area are denoted by the capital letters P and A, and are measured in persons [pers] and square meters [m^2] respectively; the symbol dA/dt denotes the net stock accumulation. The flows express the amount of floor area that in a given period of time (nominally a year) enters the stock, leaves the stock or re-circulates inside the stock. These are named new, demolition and renovation area flows respectively, are represented in small letters by new_A, dem_A and ren_A respectively and are measured in square meters per year [m^2/y]. Inputs to the model are divided in time series data and parameter functions. Time series data are required for: population P, expressed in persons [pers], population density P_D, expressed in average number of persons per dwelling [pers/dwe], and area density A_D, expressed in average square meters of floor area per dwelling [m^2/dwe]. Parameter functions affecting the behaviour of the model are: the estimated lifetime of buildings L, and the estimated interval of renovation for a given material or building's subsystem R.

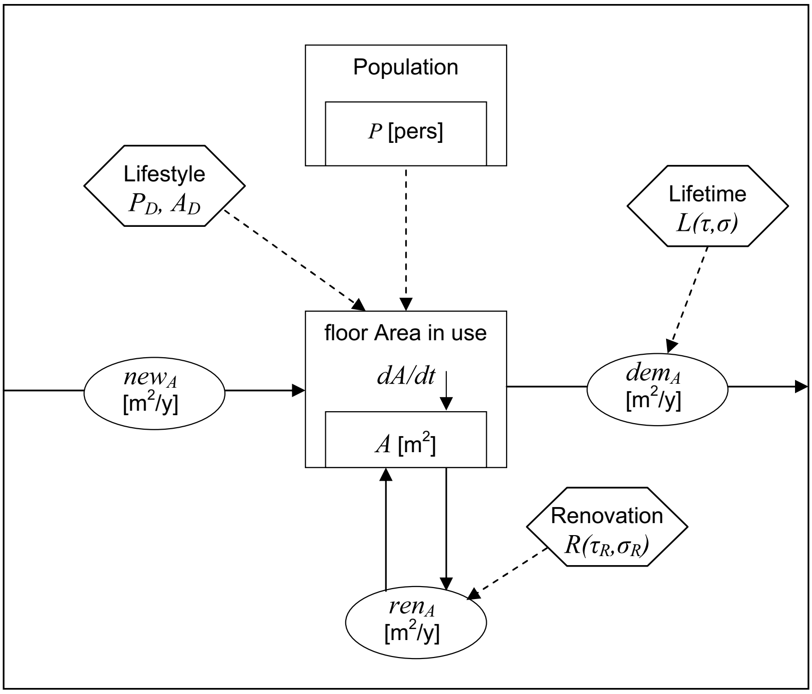


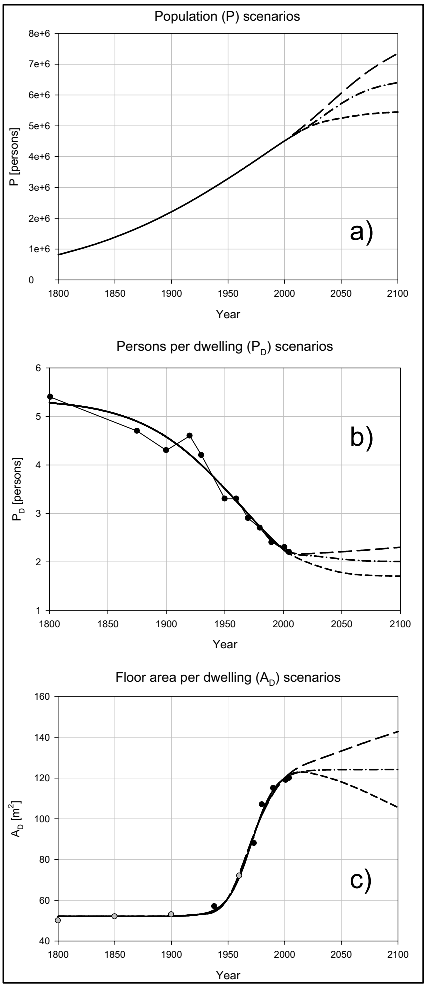
Figure 6.1 **Conceptual outline of the stock dynamics model.**

The balance equation is given in equation (6.1):

$$\frac{dA(t)}{dt} = new_A(t) - dem_A(t) \tag{6.1}$$

It follows from equation (6.1) that the new floor area *new*$_A$ has to make up for both demolition activity *dem*$_A$ and additional demand of floor area *dA/dt*.

The size of a dwelling stock is driven by the population's demand for dwelling services that satisfy their lifestyle preferences, as the number of persons living in a dwelling and the dwelling's size. In other words the stock of floor area is a function of demographic and socio-economic lifestyle parameters. These relations are also acknowledged in Kohler and Hassler (2002), and estimation of stock and flows of dwellings by demand for dwelling services is applied in both Müller (2006) and Johnstone (2001a). In the model the two inputs persons per dwelling P_D and average size of dwelling A_D represent the lifestyle preferences of the population. It is out of the scope of this work to analyse the socio-economic context from which such preferences emerge. The input data series P, P_D and A_D are simply acknowledged from historical data sources and different scenarios are considered for future projection as presented graphically in Figure 6.2. The data are essentially the same data presented by Bergsdal *et al.* (2007b), and reference is made to this article for a more detailed description of the data sources. Equation (6.2) gives the stock of floor area as the product of population and lifestyle indicators:


Population (P) scenarios

Persons per dwelling (P_D) scenarios

Floor area per dwelling (A_D) scenarios

Figure 6.2 Input data to the model:
***a)* population,**
***b)* persons per dwelling,**
***c)* average floor area per dwelling.**

$$A(t) = P(t) \cdot \frac{1}{P_D(t)} \cdot A_D(t) \tag{6.2}$$

One difference adopted in this paper regards the data on population. While in Bergsdal *et al.* (2007b) the data for population are exactly as given in the statistics, in this paper they are interpolated by means of linear regression in order to smooth out the curve in the same fashion as for the other input data series. This feature is beneficial because the method involves the calculation of the stock's derivative dA/dt, see equation (6.1); derivatives of non-smooth curves could present punctual spikes that are meaningless for the long term behaviour while may compromise the readability of the graphs.

The input data series in Figure 6.2 are given for the period 1800 until today, and with three different scenarios for the future until year 2100; named High, Medium and Low scenario. The High and Low scenarios represent a final value in 2100 of +/- 15% compared to the Medium scenario.

Once the stock of floor area is known it is possible to calculate the stock change as its derivative dA/dt. Specifically, if in a numerical implementation dt is assumed equal to one year then dA/dt represents the yearly variations in the stock. Hence, assuming for the moment that the demolition activity dem_A in one year is known, the construction activity new_A for that same year is easily deduced from the balance equation, see equation (6.1).

The demolition activity is a function of the previous construction activity and the expected lifetime of a building. Then, in order to calculate the flow of demolished floor area dem_A in a specific year it is necessary to know the flow of new area new_A for all previous years and the corresponding expected lifetime of buildings. Literature on the buildings' lifetime shows that this is a quite difficult issue to deal with and availability of data is limited. Buildings have a long lifetime and so it is difficult to find data that go back in time enough to observe the entire history of a building stock; often, analyses found in literature are based on a relatively small sample of buildings. One such approach is found in the study of Bohne *et al.* (2006) on the Norwegian dwelling stock. To what extent the observations made on a restricted group of buildings can be generalized to the entire stock is unclear. Lifetime distributions are often approximated with different functions, such as Normal, Log-Normal, Weibull, Gompertz, see for example Bohne *et al.* (2006), Johnstone (2001b) and Müller (2006). For reasons of simplicity, and in the absence of better estimations, the authors decided to adopt a Normal distribution function. A Normal distribution function is completely defined by two parameters: the mean τ and the standard deviation σ. There is no agreement between different studies on what values should be used for τ and σ. Concerning the Norwegian dwelling stock Bohne *et al.* (2006) suggests an expected lifetime of 126 years. Bergsdal et al. (2007b) use two scenarios with 75 and 125 years, and also attempt an approach where the lifetime varies between 150 and 95 years for buildings of the oldest and most recent constructions respectively. In this paper the authors decided to use the values of τ = 75, 100 and 125 respectively for the low, medium and high scenarios. Furthermore, in all scenarios it is assumed $\sigma = \frac{1}{4}\tau$. The resulting lifetime profiles are presented graphically in Figure 6.3. By applying lifetime scenarios with a wide range of values, it is possible to cover a large span of demolition outcomes. It follows naturally that with longer lifetime the demolition activity will decrease, and the renovation activity will increase due to its cyclic behaviour (see later). In general, the relatively low demolition activity experienced in the past can not be expected to be sustained in the future, as the current building stock is relatively young (post World War II). A considerable increase in future demolition activity will have major implications on material use, energy consumption, waste generation etc. Analysis of the effects of such a development and the possible measures that could be taken is left for future work.

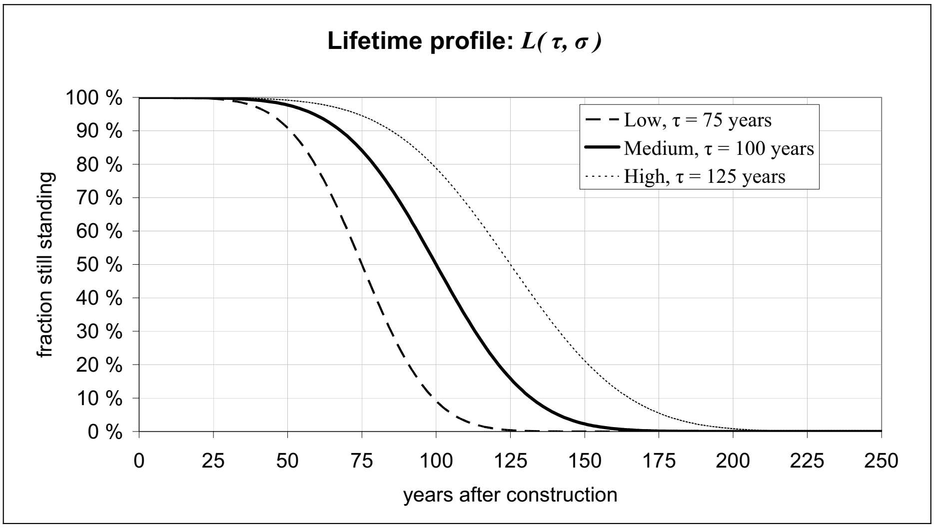


Figure 6.3 **Lifetime profile: the probability of a general square meter to be found still standing in the stock as a function of time since its construction.**

The lifetime profile *L* is defined as 1 – Normal cdf (cumulative distribution function). The associated Normal pdf (probability density function), which is simply the derivative of the Normal cdf, gives the demolition profile. The demolition profile is here named *D* and is shown in Figure 6.4.

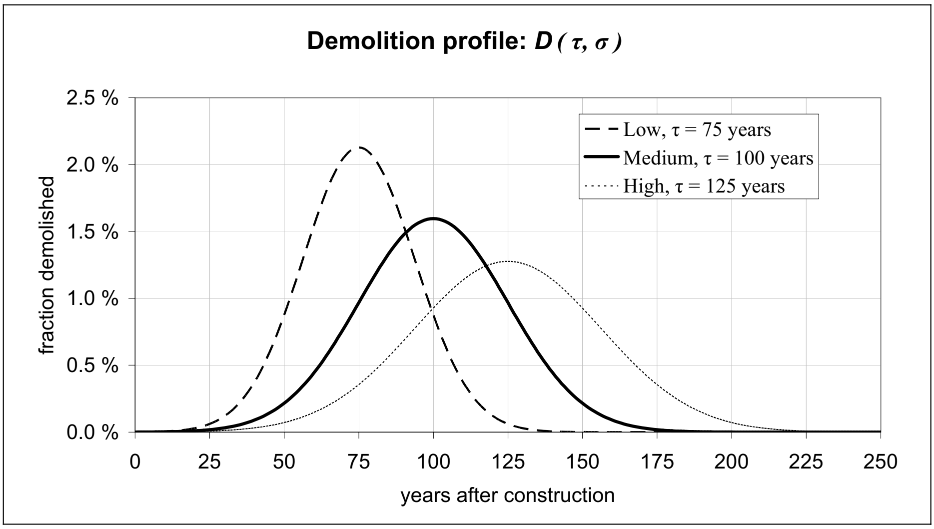


Figure 6.4 **Demolition profile: the probability associated with the demolition activity.**

In order to understand how the demolition activity in any given time *t* depends from all previous constructions, as an intuitive approach the reader can imagine translating the demolition profile function *D* of Figure 6.4 over the construction flow new_A from the initial time of simulation t_0 until the present time of simulation *t*. to expresse this concept mathematically requires introducing the concept of convolution. Convolution is a mathematical operator between two functions, *f* and *g*, often denoted as *f* **g*, that in a sense expresses the amount of overlap of one function as it is shifted over the other. The convolution of *f* and *g* over a finite period of time $[t_0, t]$ is formally written as

$$f * g \equiv \int_{t_0}^{t} f(t') \cdot g(t - t') dt' \qquad \textbf{(convolution)}$$

Even though the reader might not be familiar with this concept, convolution is a standard mathematical operation used in many fields, especially in signal processing. It is out of the scope of this paper to give an explanation of the mathematical meaning of such an operation in exact terms; for such a purpose reference is made to mathematics textbooks and manuals, as for example Kreyszig (2006). In addition, as a certain stock already exists at the initial time of simulation t_0 (in year 1800), the demolition has to account also for this initial stock $A(t_0)$. The composition and the age of the initial stock are unknown, so it is difficult to make motivated assumptions. Here it is simply assumed that it is demolished at a constant rate for 100 years; this is equivalent to state that the initial stock has an average lifetime somewhat shorter than new constructions built in the starting year, see Figure 6.3. This simplified approach is sufficient in the case of Norway (and possibly most other countries), because the initial stock is very small compared to later periods. Therefore, possible errors from this assumption have a very small impact on the demolition rate in later periods.

It is then possible to calculate the demolition flow dem_A as in equation (6.3):

$$dem_A(t) = D_0(t) + D * new_A = D_0(t) + \int_{t_0}^{t} D(t', \tau, \sigma) \cdot new_A(t - t') dt' \qquad \textbf{(6.3)}$$

where $D_0(t)$ represents the demolition of the initial stock, and is equal to $A(t_0)/100$ for the first 100 years of simulation (1800-1900), and zero otherwise. Equation (6.3) expresses mathematically the fact that the demolition in a specific year is given by the sum of all those constructions from previous years that have now reached their end of life, according to their demolition profile. Therefore, knowing all the values of construction activity new_A until the generic year *i* allows to calculate the demolition activity value dem_A for the coming year $i+1$; which in turn allows to calculate the construction activity new_A in year $i+1$ from the balance equation, and so forth in an iterative process.

Calculation of the renovation activity flow completes the model. The renovation activity is calculated in parallel to the other activities, so that its value does not affect the other flows. Data availability on renovation activity is also poor, and generally the issue is even more problematic than for demolition. Renovation activity can be cyclic, and this feature will be addressed later. First of all the term renovation activity has to be defined. In principle, each material, component, building's subsystem or energy aspect can be considered independently, because they are characterized by different life cycles; e.g. wood façades have a different lifetime than roofs, and windows have a different lifetime than heating boilers. The model does allow considering more renovation activities in parallel by defining several renovation flows, namely ren_{A1}, ren_{A2}, ren_{A3} and so on. The renovation intervals for each flow should be found empirically. Nevertheless, as the goal of this paper is to focus the attention on the methodology, only one renovation flow is shown as an explanatory case.

In the model the renovation activity has to be represented by means of some probability function, the same way as the demolition activity is treated. This function is named R and is again chosen to be a Normal pdf (probability density function). In order to show an explanatory case that is at the same time relevant, the choice of τ_R value is based on the following argumentation. The focus on renovation is aimed to serve as a basis for future analysis on materials and energy demand of residential buildings, and the relative opportunities to improve buildings' energy performance through renovation. From a study on the energy demand in the life cycle of buildings (Sartori and Hestnes, 2006) that reviewed a number of scientific articles for a total of 60 cases from 9 countries, it emerges that it is largely accepted as common practice to perform energy analysis over a period of 30 to 50 years. This because it is generally assumed that after such a period an average building is either demolished or undergoes major renovation works that will considerably alter its energy performance. A simplified approach to energy demand analysis could consider an average time after which the overall energy demand itself is "renovated". This is of course an approximation, but would allow concentrating all the possible variations in energy consumption in a single overall energy performance parameter that can vary over time according to a given renovation flow. Therefore, to the extent that the above approximation can be considered valid, the renovation flow presented here can be regarded as representative of those major renovation works that allows altering considerably a building's energy performance. A value of $\tau_R = 40$ years is chosen as central guess. Once again, due to uncertainty, instead of a single estimation three scenarios are given for $\tau_R = 30$, 40 and 50 years; each assuming $\sigma_R = \frac{1}{4}\,\tau_R$, see Figure 6.5. It may be argued that with small mean values the probability function would need to be asymmetric, in order to avoid renovation activity in the first years after construction. However, such details are left for further improvements in future work, and the Normal function is adopted here.

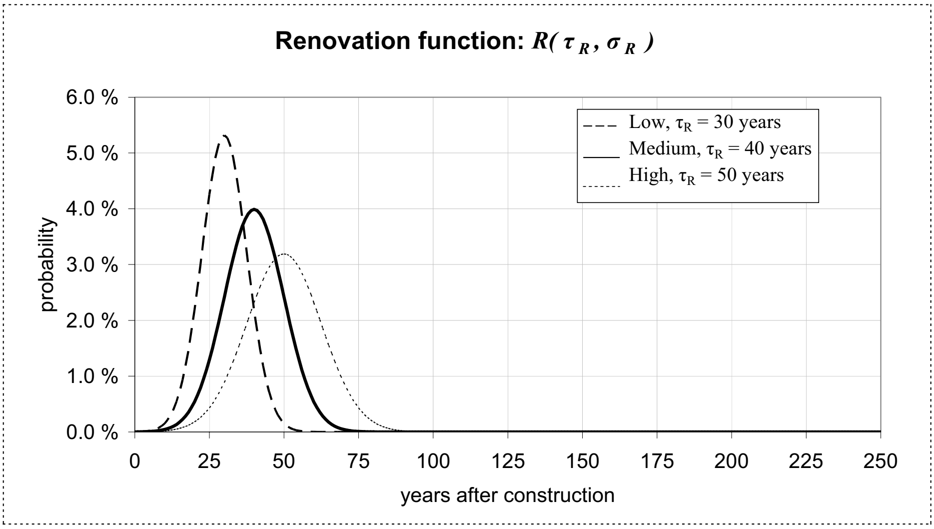


Figure 6.5 **Renovation function: the probability associated with a single round of renovation activity.**

While demolition can take place once, renovation can take place several times during the life cycle of a building. Nevertheless, the probability of a general square meter in the stock to be renovated need to be weighted against the amount of building mass that is still standing. Moreover, it needs to be weighted against the amount of building mass that is expected to remain standing long enough to justify renovation works. In other words, the model should not simulate to renovate a building today and demolish it tomorrow. To account for this fact, the authors assume that a reasonable period of expected lifetime after renovation is, at least, equal to the renovation interval itself. This will give a renovation profile that is damped over the course of time. The cyclic renovation profile R_C is given by equation (6.4) as the result of periodical repetitions of the renovation function R, weighted against the lifetime profile L shifted τ_R forward to prevent premature demolition of renovated buildings:

$$R_C(t,\tau,\tau_R,\sigma,\sigma_R) = \sum_{k=1}^{N} R(t,\tau_R \cdot k,\sigma_R) \cdot L(t+\tau_R,\tau,\sigma) \qquad \textbf{(6.4)}$$

where k is the renovation round and N is the maximum number of renovations allowed. The result is shown graphically in Figure 6.6 for the medium scenario with τ = 100 years and τ_R = 40 years.

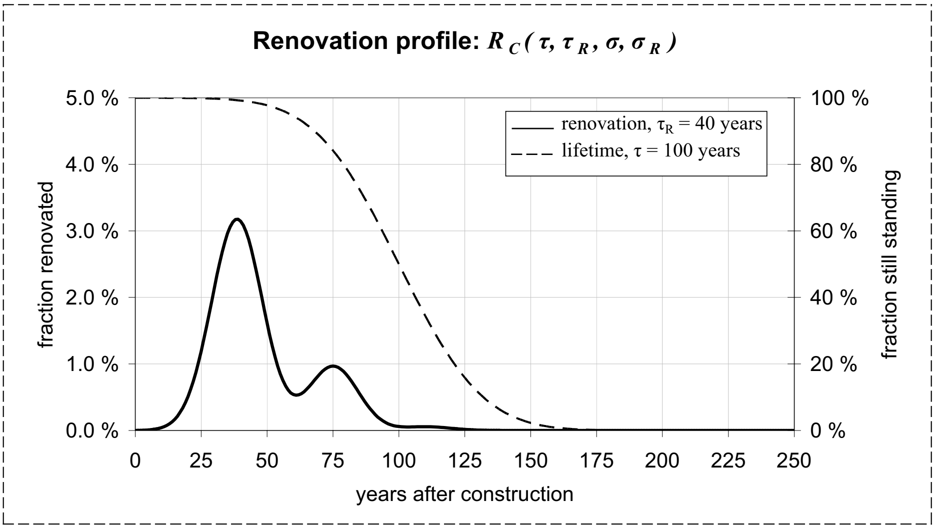


Figure 6.6 **Renovation profile: the probability associated with weighted periodical rounds of renovation activity (left *y*-axis); compared with the lifetime profile (right *y*-axis).**

Similarly to what happens for the demolition flow, the renovation flow is given by a convolution of the input flow with the probability function that describes it, the cyclic renovation profile, as in equation (6.5)[5]:

$$ren_A(t) = R_C * new_A = \int_{t_0}^{t} R_C(t', \tau, \tau_R, \sigma, \sigma_R) \cdot new_A(t - t')dt' \qquad \textbf{(6.5)}$$

It is worth noting that while the area under the demolition profile curve is equal to 1 by definition (a building can be demolished only once), the area under the renovation profile curve can be higher than one. Its value can be calculated and is here named "renovation number" N_R; it tells how many times the average square meter in the stock is renovated. For the medium scenario the renovation number is $N_R = 1.01$; meaning that while some buildings are never renovated others are renovated twice, and a few even more times, giving an equivalent figure of 1.01 renovations per each square meter in the stock, from its construction till its demolition. Scenarios with high/low renovation intervals or high/low lifetime profiles will give renovation numbers that are higher or lower than one, depending on the case.

As a final remark it is worth underlining that the definition of lifetime profile is exogenous to the model; it is known a priori and it is not affected by renovation activity. It may be argued that in reality buildings that are renovated more often are also likely to

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[5] the possible renovation of the initial stock is intentionally omitted. Considering it would have changed the results only for the first 100 years of simulation (1800-1900), as the initial stock is extinguished in such time. Changes in this period are of no interest for forecasting purposes and anyhow have no effect on the flows development because in the model construction and demolition flows are independent from the renovation flow, which is as well independent from its past values.

live longer. This sort of cause-effect relation is not included in the model, but the same relation can be observed in the results. In fact, if a longer lifetime is assumed then the renovation activity will increase because more cycles of renovation find place within the given lifetime.

6.4 Results and discussion

This section presents the results obtained by running the model in different scenarios and shows the evolution of stock and flows from 1900 to 2100. The medium scenario is presented first; here all inputs are set at their medium scenario values. Results on stock and flows are compared with available empirical data. Subsequently, a sensitivity analysis is performed by varying each input data at a time, from its low to its high scenario values, in order to study the effect of the estimates' uncertainties. Two groups of graphs are presented: one for the input data series P, P_D and A_D, and one for the input parameters L and R. Data from all the simulations are presented in Table 6.3. The main emphasis is on the renovation activity, and the reader is referred to Bergsdal et al. (2007b) for a more detailed discussion about the stock and flows of construction and demolition.

6.4.1 Medium scenario

The results for the medium scenario are shown in Figure 6.7. While population growth in the last century has been nearly linear and is expected to continue to be so at least until around year 2050, the two lifestyle indicators P_D and A_D are expected to level off in the future, see Figure 6.2. Due to this levelling off the stock will continue to increase but at a lover pace than what it has experienced in the past. This slowing phase has started already in the last two decades. Hence, the steep slope that the construction activity new_A has presented since roughly the end of World War II peaks in the middle 1980s and then starts to decline until today and up to around year 2025.

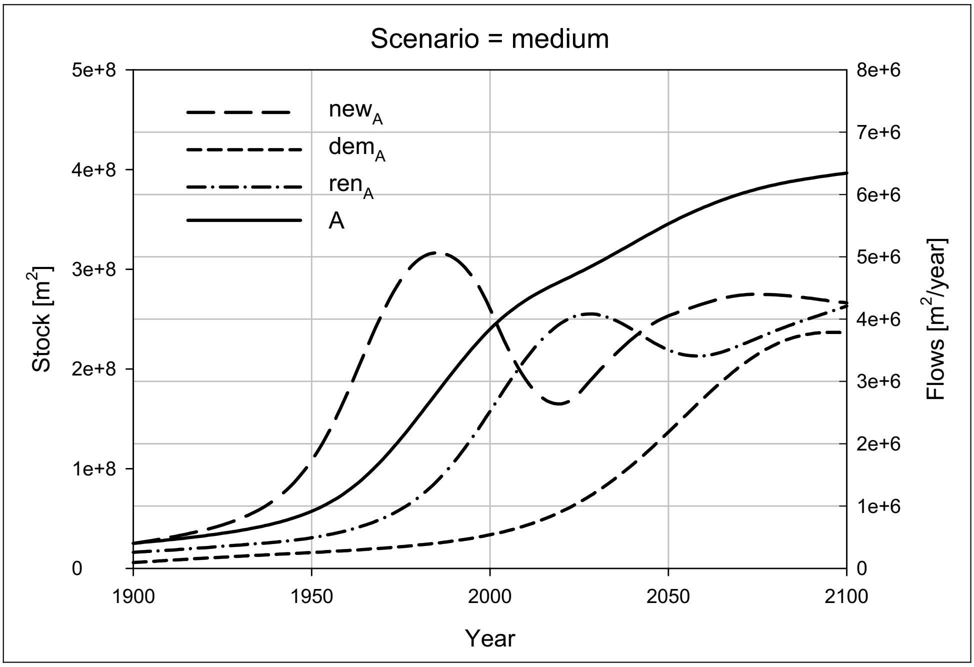

Figure 6.7 **Stock and flows evolution for the medium scenario.**

Because of the long lifetime of dwellings, τ = 100 years in the medium scenario, the peak of construction will produce a peak of demolition activity dem_A toward the end of the century; this peak will be less pronounced because of the variance σ of the lifetime profile L. In turn, increased demolition activity will call for increased construction activity in order to substitute the demolished floor area. Construction activity also has to meet an increasing demand, but as the stock seems to stabilize toward year 2100, the input and output flows will tend to have the same value. Also the renovation activity ren_A is expected to increase as an effect of the initial construction peak, with a first peak delayed of about 40 years, according to the renovation interval. In the long run, as all the other variables seem to stabilise toward the end of the century, also renovation activity will converge to roughly the same value of construction and demolition. This is the combined effect of the stabilised stock and the renovation number equal to one. Nevertheless, it is worth noting the time evolution for the coming decades: construction activities are declining while renovation activities are increasing. The model shows that around year 2010 renovation is expected to overtake construction and become the principal building's related activity for the remaining three decades, until over 2040.

6.4.2 Comparison with empirical data

The results of the medium scenario can be compared against available data on the Norwegian dwelling stock and activities of construction, demolition and renovation. The Norwegian bureau of statistics, Statistics Norway, has regularly published censuses on population and housing since 1900 with ten years period (Statistics Norway, 2001a) which contain data on the number of dwellings in stock based on a complete census. Unfortunately, data on size of dwellings are available only in the last editions of the census for 1980, 1990 and 2001; these records are shown in Table 6.1 in comparison with the model values.

Table 6.1 Total floor area in the stock, Census vs. Model.

year	Censuses[a] approx. total [m^2]	Model approx. total [m^2]	Difference %
1980	135 000 000	148 000 000	9.6%
1990	184 000 000	194 000 000	5.4%
2001	238 000 000	239 000 000	0.4%

[a] Statistics Norway (2001a)

Data for P and P_D are taken from the censuses, see Bergsdal *et al.* (2007b), with the only difference that smooth curves rather than the original data points are used, see Figure 6.2 *a)* and *b)*. The empirical data used to derive the A_D curve, instead, are collected from surveys of housing conditions made on relatively small samples of dwellings (some thousands) and not on the entire stock, see Bergsdal *et al.* (2007b). These considerations can explain the difference between the censuses and model values for total floor area in the stock.

For construction activity yearly records since 1946 are available from Statistics Norway (2007a, b). As shown in Figure 6.8, the model seems to be able to reproduce quite faithfully the behaviour of the construction activity when looking at the long term trends while ignoring short term fluctuations; this is a positive feature of the model. Nevertheless, data on floor area from the model look generally higher than those recorded in the statistics for both stock and new construction.

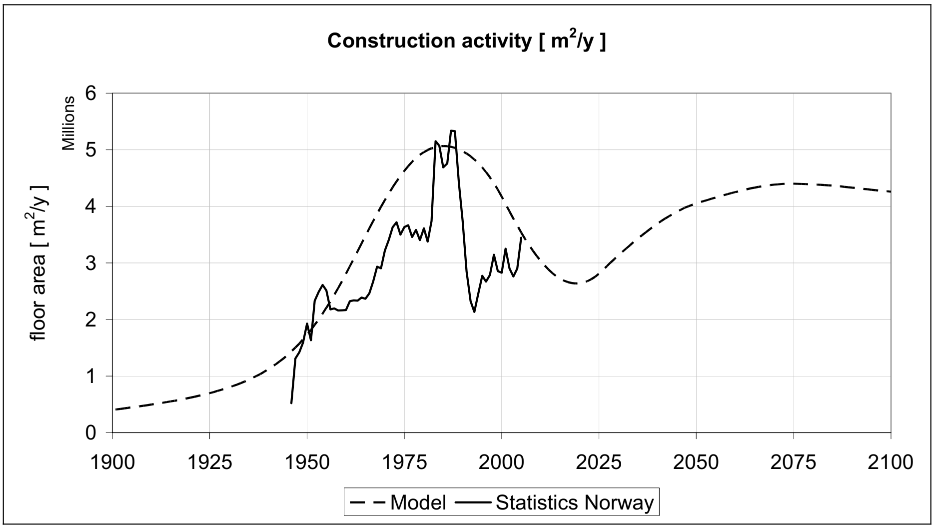

Figure 6.8 Construction activity in the model and in statistics (Statistics Norway 2007a, b).

There are three factors that can justify the model's overestimation of new floor area. First, as mentioned the assumed average size of dwellings in the model A_D, see Figure 6.2 *c)*, is derived from surveys conducted on relatively small samples of dwellings and so the input A_D may be an overestimate itself. Second, the shape and magnitude of the new_A curve is affected by the assumed function expressing the lifetime of buildings. Differences between the actual lifetime of buildings and the assumed lifetime profile L may then also be responsible for the observed overestimation. Third, statistics on floor area include only new constructions. In the model, instead, the flow new_A is meant to account for all new floor area that comes into the stock in order to satisfy a higher demand. Part of the additional new floor area may come from extension of existing buildings or simply by converting into living spaces parts of the building that were originally not counted as living area (e.g. basement or loft).

Concerning demolition and renovation activities, unfortunately, no comprehensive data sets were found for comparison. The data collected from literature are summarized in Table 6.2 and compared with the model's results.

Table 6.2 Summary of data comparison for demolition and renovation activities.

Source	Period	Demolition [m^2/y]	Renovation
Myhre (2000)	1998 – 2030	530,000	---
Model	1998 – 2030	450,000 – 1,200,000	---
Rønningen (2000)	1998	---	77 % of new constructions [m^2/y]
Model	1998	---	52 % of new constructions [m^2/y]
Statistics Norway (2006)	Total 1971 – 2001	---	50 % of 2001 stock [dwellings]
Model	Total 1971 – 2001	---	19 % of 2001 stock [m^2]

Regarding demolition, the results of the model appear to be in line with those reported by others. In his report Myhre (2000) estimated that in the period from 1983 to 1995 the number of dwellings demolished oscillates between 3,000 and 5,000 per year, corresponding to 300,000 – 500,000 m^2. He used a value of 530,000 [m^2/y] for projections until 2030. He also reported that Rødseth *et al.* (1997) estimate dwellings departure to be 7,000 units toward 2015. Results from the model lie in the same range, but marking an increasing trend from 450,000 to 1,200,000 [m^2/y] in the period from 1998 to 2030.

Regarding renovation, the results of the model appear to be an underestimate compared to other sources; this is remarkable, considering that renovation flow already turns out to be the most significant one in the model for the years ahead. Rønningen (2000) bases his study on economical evaluations of cost per square meter in new buildings and in renovation projects, and concludes that in year 1998 renovation activity in square meters corresponded to about 77 % of new constructions in the same year. He also emphasizes that this covers only officially reported renovation projects, and the numbers are therefore uncertain and the real renovated surface area might be higher. The equivalent figure calculated in the model gives 52 % for the same year. It might be argued that the value reported by Rønningen could be affected by yearly fluctuations. However, it is possible to compare also the cumulative renovation activity with other sources. Statistics Norway censuses usually do not report data on either demolition or renovation; data on renovation were collected for the first time only in the census of 2001. The respondents were asked to specify when the last round of renovation was performed, specifying that:

> "Extensive improvements and renovation are defined as major work that has been carried out to raise the standard of the dwelling." (Statistics Norway, 2001b)

The figures collected were not complete, so they were not officially published in the Census 2001 report; nonetheless, it was possible to access that information by personal communication with Statistics Norway. From Statistics Norway (2006) it emerges that in the period between 1971 and 2001 a total of at least 983,323 dwelling were renovated, plus a number of 263,886 "don't know" respondents. Considering that the Norwegian dwelling stock in 2001 consisted of a total of 1,961,548 dwellings (as recorded in the same census) the resulting figure is quite outstanding: 50% of the building stock has been renovated in the course of the past 30 years. On one hand, this might suggest that the probability density function for renovation, see Figure 6.5, should have its mean at 30 years rather than 40, causing then a higher renovation flow in the model. On the other hand, caution has to be used in reading the results from the census. Indeed, it is not clear how the respondents might have interpreted the "major work that has been carried out to raise the standard of the dwelling". Nevertheless, it remains a fact that the model's estimate, even though not directly comparable because expressed in m^2 rather than in number of dwellings, is clearly lower: 19 % of building stock renovated in the last 30 years.

6.4.3 Scenarios with input data series

The driving force for the dwelling stock is the population's demand for floor area of living. Strong national economic growth in the last 50 years is reflected in higher living standards and subsequently higher demand for floor area. This growth is demonstrated in the general development in P, P_D and A_D for the last 50 years, and the resulting increase in construction activity and stock size for the same period. However, the trends in A_D and P_D have shown signs of levelling off in the last years, and the scenarios assume a similar trend for the future; implying decreased future growth levels for the dwelling stock compared to the last 50 years.

Historical results should be equal for all scenario variations. However, there are slight deviations in the regression curves for the input data series although they are too small to be identified in the graphs in Figure 6.2. As a result, minor deviations can also be found in the result graphs in Figure 6.9. The effects on the results are however negligible.

Population scenario results, *P*

The upper part of Figure 6.9 shows simulation results for high and low scenarios for population P. Population growth is a fundamental driver in the dwelling system, and the results demonstrate this. While the stock stabilizes towards 2100 in the low scenario, the stock continues to grow rapidly in the high scenario. Relative to the medium scenario, the 2100 stock values will be 115% and 85% for the high and the low scenario respectively. The same figures are 124% and 88% for construction. Demolition activity is the result of previous stock demand and construction activity, and due to the long lifetime of dwellings, the effects on demolition activity are not very strong.

Regarding renovation activity, both scenarios predict that this will surpass construction activity within the next few years. In the low scenario it will remain so for nearly half a century. The first renovation peak is mainly a consequence of the high construction activity in the last decades, and the peak values are therefore almost the same for the two scenarios. Population growth thereafter plays a more important role with respect to renovation activity. The high scenario experiences continued and strong growth for the last four decades, ending at 115% of the medium scenario, whereas the corresponding value is 81% in the low scenario.

Persons per dwelling scenario results, P_D

Applying high and low scenarios for persons per dwelling P_D gives similar main trends as for population. However, the development in construction activity in the low scenario shows considerable differences from the high and medium scenarios. The decrease in construction activity in the next 15-20 years is much less pronounced for the low scenario, due to less rapid changes in the future P_D values.

Regarding renovation, two features distinguish the low scenario for P_D from both the high scenario and the scenarios for the other input data series. First; whereas the timing of the first renovation peak remains the same, the low scenario does not experience a subsequent decline. Renovation activity remains at a stable level before increasing and then stabilizing again towards the end of the century. Second; renovation never exceeds construction activity.

Floor area per dwelling scenario results, A_D

Assumptions about the average size of dwellings prove to be very important. Whereas the stock increases strongly in the high scenario, it is actually decreasing towards 2100 in the low scenario, implying more demolition than construction. Since demolition is the least affected activity, the main influence is to be found in construction activity; ending at 120% and 75% of the medium scenario for the high and the low scenarios respectively.

The renovation curve for the high A_D scenario resembles the one for the high P scenario. In both cases there is a strong and continued growth in the dwelling stock, and the resulting increase in construction activity from around 2020 is reflected in increasing renovation activity one renovation interval later. The decrease in stock size in the low scenario takes place too late for its influence to be seen on renovation activity; the effect will show after 2100.

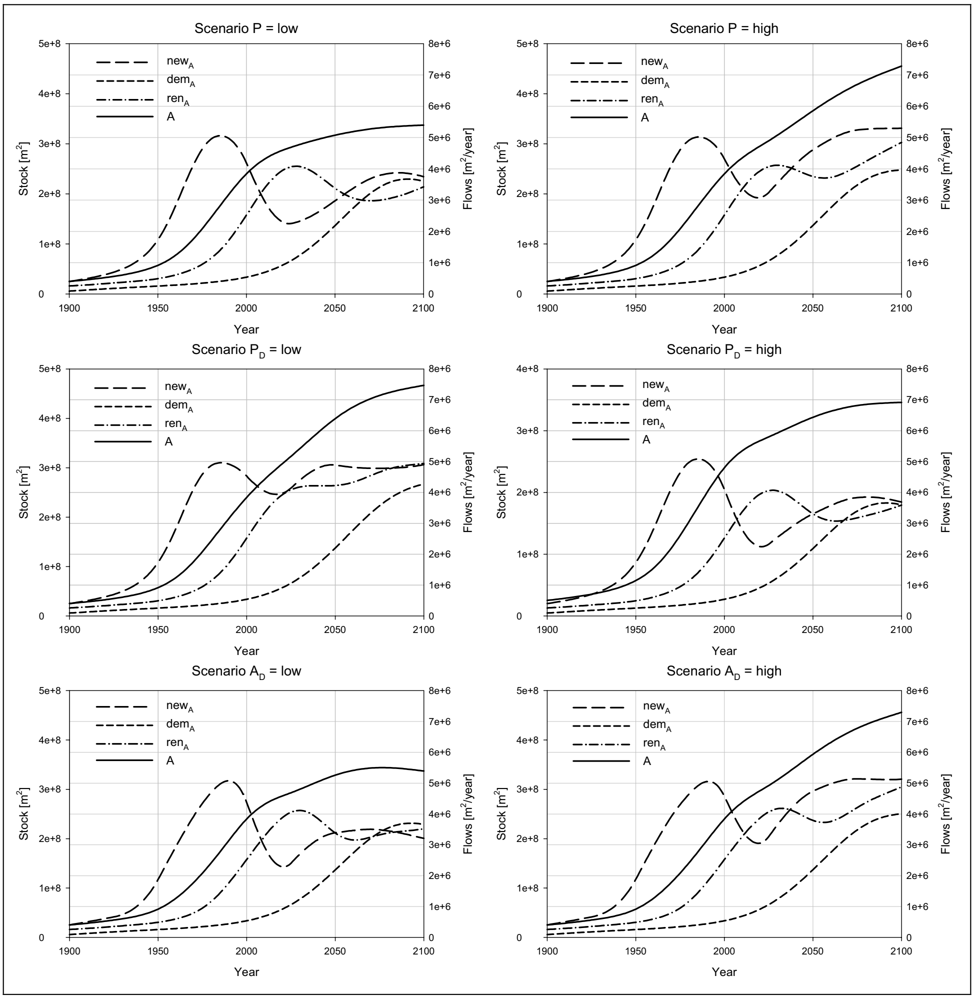

Figure 6.9 **Simulation results I: sensitivity analysis on input data series.**

6.4.4 Scenarios with input parameters

Scenarios for the input parameters include varying the expected average lifetime τ of residential buildings and the average renovation interval τ_R. Simulation results are presented in Figure 6.10, with lifetime scenarios in the upper part and renovation scenarios in the lower part.

Lifetime scenario results, *L*

Alteration of the lifetime assumptions affects both the timing and magnitude of the construction and demolition peaks, and of the renovation rounds. Stock size is however not affected, as the population's demand for dwelling services (in m^2) is independent of building lifetime in the model. The fluctuations are more rapid and more pronounced in the low scenario. Demolition activity increases as buildings are taken down earlier in the low scenario, and as stock demand is unchanged construction activity will also increase in response to the higher demolition rate. The activity levels are considerably different for a longer building lifetime, demonstrating the much slower turnover of floor area accompanied with a long lifetime. Table 6.3 shows that the largest deviations are not found in 2100, as for the input data series, but rather in 2050. It is the demolition activity that is affected the most, with 2050 values of 52% and 183% of the medium scenario in the high and the low scenario, respectively. Whereas the next peaks in construction and demolition occur around 2060 in the low scenario, the peaks are delayed until the next century in the high scenario. As σ is set to ¼ of τ, the activity distributions are also more dispersed in the high scenario.

Renovation activity levels are strongly affected by lifetime scenarios. Renovation is by far the dominating activity for the entire forecasting period in the high scenario, while even demolition will be considerably higher than renovation in the low scenario from about 2020. This simply reflects the fact that only when buildings live for a long time renovation activity is consistent. Another way to look at it is with the renovation number N_R. Whereas N_R is 1.01 in the medium scenario, the same figures are 1.63 and 0.42 for the high and the low scenario, respectively. Relative to the medium scenario, the activity levels are 120% and 62% for the high and the low scenario, respectively. In 2050, the effect is even more pronounced with the same values being 146% and 48%. The 40 year renovation intervals are clearly seen in both scenarios.

Renovation scenario results, *R*

Stock size and levels of construction and demolition activity are independent of the renovation intervals and are therefore not affected in the renovation scenarios, i.e. their graphs are the same as in the medium scenario in Figure 6.7.

Variations in the renovation interval τ_R are, as expected, of considerable importance for both the timing and magnitude of renovation activity. The low scenario with $\tau_R = 30$ years has a considerably higher renovation activity throughout the entire time horizon of the simulations, and especially for the future projections. Lower τ_R value in the low scenario implies a more rapid replacement of materials and building components. The peaks in renovation activity therefore appear sooner than in the high scenario, and as lifetime is unchanged, the renovation number N_R and total renovation activity increase. Whereas N_R is 1.01 in the medium scenario, the same figures are 0.54 and 1.84 for the high and the low scenario, respectively. Relative to the medium scenario's value renovation activity level in 2100 is 56% for the high scenario and 177% for the low scenario respectively. In the high scenario renovation levels are so low that from around 2050 demolition becomes higher.

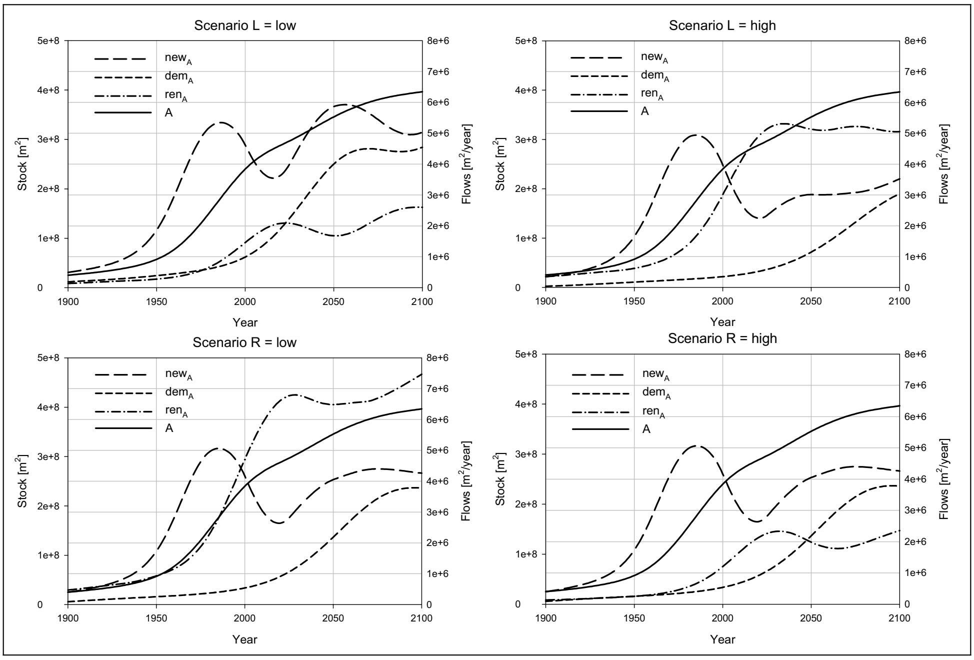

Figure 6.10 **Simulation results II: sensitivity analysis on input parameters.**

6.4.5 General considerations

Renovation activity has become increasingly important and follows the growth of stock and construction activity. For all input data series scenarios, except low P_D, renovation will take over as the dominant activity in the next decades. Varying τ and τ_R, instead, has a dual effect. Short lifetime or long renovation intervals result in low renovation activity, while the opposite is the case for long lifetime or short renovation intervals that generate high renovation activity. However, regardless of the scenario, renovation activity is expected to increase in absolute figures in the nearest decades because of the peak in construction activity in the 1980s.

With the exception of the low scenario for A_D, stock is increasing for the entire projection period. This also implies that demolition activity is always lower than construction activity. However, as the input data series level off towards 2100, stocks will be growing less; at the same time demolition increases and construction decreases or flattens out, so that the two curves will show signs of converging.

Table 6.3 presents a comparison between magnitudes of stocks and flows, in percent, for the different scenarios relative to the medium scenario in 2050 and 2100. The upper part of the table shows the numerical values for the medium scenario in the same years.

Scenarios for the input data series show that deviations from the medium scenario values generally become larger with time, both for the high and the low scenarios, although with a few exceptions. The delay related to demolition is clearly seen in the table, with changes being close to zero in 2050, but increasing towards 2100. Scenario results for the input data series give a deviation range of 85-118% for stock size and a corresponding range of 73-124% for construction activity. The same figures are 95-113% and 81-121% for demolition and renovation, respectively.

The effects of changing the input parameters τ and τ_R are more dramatic. Lifetime scenarios have a deviation range of 74-145% for construction and 52-183% for demolition. The same range is 48-146% for renovation. As opposed to the data input scenarios, the lifetime scenarios have their largest deviations from the medium scenario in 2050. Changing the renovation intervals directly affects the renovation activity the most. The deviation range is 56-185% for the renovation scenarios. Stock size, construction and demolition activity are not affected in these scenarios.

Table 6.3 **Scenario results relative to the medium scenario.**

		Medium	
	Stocks/flows	**2050**	**2100**
Floor area	A (m^2)	3.45E+08	3,96E+08
	new_A (m^2/year)	4.05E+06	4.26E+06
	dem_A (m^2/year)	2.19E+06	3.78E+06
	ren_A (m^2/year)	3.50E+06	4.21E+06

Input variation		**Low**		**High**	
	Stocks/Flows	**2050**	**2100**	**2050**	**2100**
Population, P	A (%)	92	85	106	115
	new_A (%)	73	88	114	124
	dem_A (%)	100	95	100	105
	ren_A (%)	96	81	107	115
Persons/dwelling, P_D	A (%)	116	118	93	87
	new_A (%)	121	115	82	87
	dem_A (%)	101	113	100	95
	ren_A (%)	121	117	94	85
m^2/dwelling, A_D	A (%)	95	85	107	115
	new_A (%)	84	75	117	120
	dem_A (%)	100	97	100	106
	ren_A (%)	97	84	108	116
Lifetime, $L(\tau,\sigma)$	A (%)	100	100	100	100
	new_A (%)	145	118	74	83
	dem_A (%)	183	120	52	81
	ren_A (%)	48	62	146	120
Renovation, $R(\tau_R,\sigma_R)$	A (%)	100	100	100	100
	new_A (%)	100	100	100	100
	dem_A (%)	100	100	100	100
	ren_A (%)	185	177	57	56

6.5 Conclusions

Forecasting of construction, demolition and renovation activities in the built environment has significant implications for policies on materials demand, energy conservation and climate change. The built environment is a dynamic system where past activity levels strongly influence the future development. This dynamic is not sufficiently understood, and this article presents an exploration of methodology for assessing both stock and flows related to residential floor area in a coherent way. The stock is assessed by social indicators such as population, average number of persons per dwelling and average size of dwellings. The flows are assessed based on assumptions on parameters such as the lifetime of dwellings and renovation frequencies.

Modelling results are compared to other sources when available. The comparison shows that construction activity might be somewhat overestimated. However, construction activity appears to be quite well represented by the model with respect to long term behaviour. Renovation and demolition activity are harder to asses because less information is available. The generally poor knowledge about these activities is exactly one of the main motives for using a dynamic model.

The dynamic behaviour of the model is clearly seen from the modelling results. The expected stabilization of lifestyle indicators will cause the stock of floor area to grow slower than in the past, even though population growth is expected to continue nearly linearly until about 2050. As a consequence the construction activity is expected to slow down in the coming decades. Nevertheless, the high construction activity recorded in the post-war period is expected to bring a substantial increase in demolition activity in the second half of the current century. In turn this will cause an increase in construction activity in order to substitute the departed units. Construction activity then is expected to increase again and remain at higher values in the second half of the century, despite the expected slowing down of population and stock growth.

The dynamic effect is also visible in the results for the renovation flow with renovation peaks delayed from the construction peaks according to the given renovation intervals. With only one exception, all the scenarios related to the input data sensitivity analysis predict that renovation will overtake construction as the dominating C&D activity within the next few years. However, construction activity will dominate again in the second part of the century. So, the dominance of the renovation activity may be a temporal phenomenon, because construction activity is expected to re-raise as the post-WWII building stock is due to be replaced. Results from the parameters sensitivity analysis are more dramatic and less uniform.

The suggested approach for renovation modelling is exemplified for major renovations of dwellings. However, the presented method allows for many different types of renovation to be modelled. Renovation related to different materials, building components or energy uses can all be modelled separately by applying different renovation intervals.

Dynamic modelling of C&D activities supply valuable information about the possible future developments in the residential sector and demonstrates the importance of considering history when making assumptions and forecasts about the future. The method also allows for investigating how variations in different input data and parameters will affect the model forecast of stock and flows of residential floor area. The required input data are relatively easy to obtain from censuses or surveys on population and housing conditions. At the same time parameters as buildings' lifetime and renovation intervals are difficult to estimate. This drawback is overcome in this method by defining probability functions and analysing different scenarios, to partially compensate for the uncertainty inherent in the definitions of those probability functions. These features are believed to make the method presented here suitable for application also to other national residential stocks than the Norwegian one. However, the data availability will vary and have to be considered in each individual case.

For future development of this work, also the non-residential part of the building stock could be modelled dynamically following a similar approach. The lifetime of these buildings is generally lower and the renovation intervals are more frequent, with the implications this has for the material and energy use and waste generation. However, modelling the non-residential building stock would require careful consideration of relevant parameters to represent the drivers in the demand for non-residential floor area. Furthermore, the non-residential building stock is comprised of a variety of building types that are less homogenous than in the residential stock, and would probably need to be disaggregated further. The drivers and the parameters might be very different than those included in the analysis of the residential building stock.

6.6 Acknowledgments

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Mid-Norway as a pilot region for promotion of passive houses: A study of the potential

Based on:
Midt-Norge som pilotregion for passivhus satsing: Potensialstudie

Wachenfeldt, B. J. and Sartori, I.

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7 Mid-Norway as a pilot region for promotion of passive houses: a study of the potential

This chapter is based on the study presented in Appendix A, originally written in Norwegian. The study was performed on a regional scale, and focuses only on the residential sector. The model used is the same as the one already introduced in chapter 5 – the energy model – when analysing the entire Norwegian building stock. For this reason, all of the original study in Appendix A is not reproduced; only those aspects that are new are presented in this chapter. One new aspect is that estimations on the activity levels are taken from the results of the model presented in chapter 6 – the activity model. Furthermore, unlike the paper presented in Appendix A, this chapter focuses also on methodological issues and not only on the results.

7.1 Introduction

According to Statnett, the Norwegian electricity transmission operator, the biggest challenges of the moment for expanding the electricity grid are related to the considerably increasing demand in the Mid-Norway area. The Mid-Norway area comprises the three regions: Møre and Romsdal, Sør Trøndelag and Nord Trøndelag. At the same time there is great uncertainty regarding the possibility to increase the production in the area. This would require huge investments on the supply side. All measures that can limit the consumption growth would contribute to limit the need for expanding the transport capacity of the grid and the need to establish new power production.

From an environmental and social economics point of view it is therefore especially interesting to investigate measures that can limit the consumption growth in the Mid-Norway region. In this study the potential for reducing the demand for electricity and other forms of energy in Mid-Norway is analysed for the residential sector. In particular, the consequences of policies for promotion of passive houses and for promotion of alternatives to electricity as a heating source are analysed.

7.2 Model

The model adopted is the same one presented in chapter 5, the energy model, based on the definition of energy as the product of activity and intensity matrices. The GAB register allows extraction of information on activity at a regional level. The GAB data updated to 2005 shows that the total amount of square meters in the residential sector in the Mid-Norway region is approximately 11% of the national stock. Data on energy consumption at the regional level are not available at the same level of detail as at the national level. However, it was assumed that the historical development of energy demand and carriers share has followed the same path as given by the national data, but scaled down by a factor of 11%. As a consequence, the definition of the archetypes is identical to the one given in chapter 5. This means that the intensity levels calculated for the national stock are assumed to be representative for the portion of the stock located in Mid-Norway too. As described in chapter 5, an archetype is defined as a statistical composite of the features found within a category of buildings in the stock. An archetype is completely defined by a combination of an energy class and a user preference on carriers used for heating purposes. The model comprises six energy classes, from E to A+, and four options for the user preference: present day average, trend values for 2035, and scenario specific values for thermal carriers and heat pumps scenarios. As only the residential sector is analysed, the total number of archetypes is 24 instead of 48. The policies studied and the scenario hypotheses made for energy class and user preference are the same here as in chapter 5. Summarizing, the three policies are: wide diffusion of thermal carriers, wide diffusion of heat pumps and wide diffusion of conservation measures. Combination of the conservation measures with the other policies is also possible. The resulting scenarios are the following:

- ***Base***: reference scenario, based on observed trends and with no implementation of any specific policy.
- ***Thermal***: scenario implementing the policy for maximum diffusion of thermal carriers.
- ***Heat Pump***: scenario implementing the policy for maximum diffusion of heat pumps.
- + ***Conservation***: implementation of the policy for maximum diffusion of energy conservation measures, adopted in addition to the other hypotheses in all three previous scenarios.

The scenarios are meant to express the maximum potential for each policy, given the constraints that the amount of square meters built new, demolished and renovated is defined a priori and is the same for all scenarios. The model simulation starts with a given existing stock. In addition, three flows of building mass are defined: new construction, demolition and renovation. Each year the new construction flow is assigned to some archetypes (or fractions of the total flow assigned to different archetypes) according to the scenario's hypotheses. The demolition flow simply leaves the stock, so it is removed from the model. The renovation flow re-circulates in the stock, meaning that no square meter is added or subtracted to the model, but there is a portion of the original building mass that "migrates" from some archetypes to others, in accordance with the scenario's assumptions. A transition period is defined for new construction from 2010 to 2015, and for renovation from 2010 to 2020. During the transition period the new and renovation flows migrate gradually from the initial to the final archetypes. The transition period is needed to simulate the time required for extensive diffusion of certain design concepts, materials, technologies and practical expertise. The transition period is assumed longer for the renovation flow to allow for new materials and technologies as well as for practitioner experience to be developed in new construction and then gradually adopted also in renovation. The transition period is also meant to represent some inertia to change in the energy system. This can be due either to the necessity to set up an infrastructure, as for district heating or gas, or simply to the fact that new habits take time to make their way into society.

In the scenarios with conservation measures all new construction is supposed to be passive houses (or class A+) at the end of the transition period, while the renovated buildings are supposed to achieve the energy efficiency of class A. Even though the renovated buildings are not supposed to reach the passive house standard, the technologies that are used to improve the energy performance are the same passive technologies as those adopted in passive houses, i.e. high insulation, highly insulating windows, air tightness of the building, efficient ventilation with heat recovery, control of solar gains, and so on. The different final result is meant to account for the fact that technical difficulties and costs are generally higher in renovation than in new construction.

The difference from the hypotheses made in chapter 5 is in the estimation of the activity flows. In chapter 5 the future activity flows were assumed to be constant; the estimations were taken from the best available data found either in literature or in statistics. In this work, instead, the estimations for the activity flows of new construction, renovation and demolition are taken from the model presented in chapter 6, the activity model. The model in chapter 6 performed a sensitivity analysis on input and parameters, resulting in multiple scenarios. The data used here refer to the medium scenario, and are reproduced in Figure 7.1 for clarity. The medium scenarios assumed an average lifetime of dwellings of 100 years, and an average interval of renovation of 40 years. The renovation interval was assumed to be representative of those major renovation works that allows for a considerable alteration of a building’s energy performance. Therefore, to the extent that this hypothesis is true, the renovation flow in Figure 7.1 is suitable to describe the renovation activity in the energy model, where the renovation is indeed meant as an occasion for improving the energy performance of a building.

The uncertainty related to the activity model assumptions and outcomes are discussed in chapter 6, and are not repeated here. Nevertheless, it is important to remember that such a model aims at capturing the dynamics of construction, renovation and demolition activities in their long term behaviour. Relative to the results for the medium scenario, as shown in Figure 7.1, the stock will continue to increase but at a lower pace than what it has experienced in the past. This is the result of a steady population growth with the two lifestyle indicators (persons per dwelling and dwelling’s area) that are expected to level off in the future, i.e. stabilizing at approximately the same values as at present. This slowing phase has started already in the last two decades. Hence, the steep slope that the construction activity experienced since the end of World War II peaks in the middle 1980s and then starts to decline until today and up to around year 2025. Because of the long lifetime of dwellings, on the average 100 years in the medium scenario, the peak of construction will produce a peak of demolition activity toward the end of the century. In turn, increased demolition activity will call for increased construction activity in order to replace the demolished floor area. Also the renovation activity is expected to increase as an effect of the initial construction peak, with a first peak delayed about 40 years, according to the renovation interval. It is worth noting the time evolution for the coming decades: the construction activity declines while the renovation activity increases. The model shows that around year 2010 renovation is expected to overtake construction and become the principal building related activity for the remaining three decades.

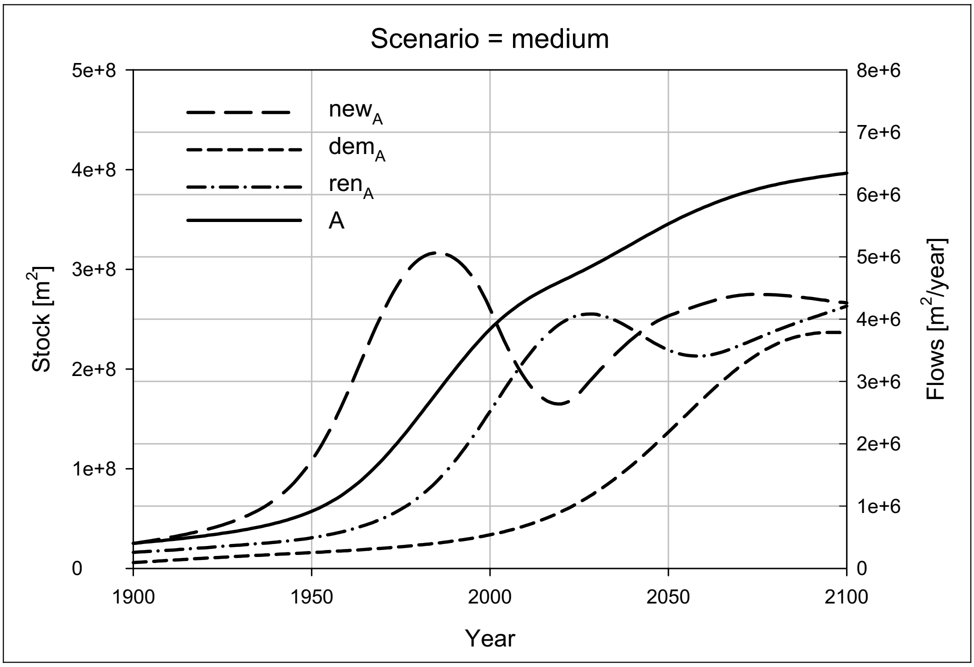

Figure 7.1 **Activity results for the medium scenario of the model presented in chapter 6. The curves represent, in the legend's order: new construction, demolition, renovation and the total stock of dwellings in Norway.**

Data on the stock from the GAB register are given in gross surface area, and for the year 2005 the number is about 321 million m^2. Applying the heated-to-gross area conversion factor defined in chapter 5, gives an equivalent heated area of about 220 million m^2. The data used as input to the model in chapter 6, instead, are collected from surveys and are measured in utility floor area. The utility floor area is somewhat higher than the heated floor area because it includes also storage rooms and rooms for technical equipment. The result is, indeed, a little higher estimation: 256 million m^2 for the stock in 2005, see Figure 7.1. Nevertheless, as has been observed in chapter 6, the resulting flow of new construction appears to be overestimated by the model when compared to statistical records (renovation and demolition flows cannot be compared the same way because of the lack of information). As an approximation, to try compensating for the observed overestimation, the results from the activity model were used directly as input to the energy model, without converting from utility to gross floor area.

In chapter 5 it was assumed that renovation and new construction flows were to be identical for the simulation period, from 2006 to 2035; this corresponded to a value of approximately 3.3 million m^2/y. Comparing this value with those in Figure 7.1 shows that there is, on the average, a substantial agreement between the two approaches. Renovation and new construction values are in the range between 2.7 and 4.1 million m^2/y. The difference is in the dynamics. While new construction is expected to decrease in the coming decades, renovation is expected to increase and become the principal activity throughout the simulation period. The demolition activity starts with values similar to those previously used in chapter 5 (about 0.6 million m^2/y), but then it is expected to increase throughout the simulation period up to 1.4 million m^2/y in 2035.

The data shown in Figure 7.1 refer to the entire Norwegian dwelling stock, and before being applied to the Mid-Norway case they were scaled down by a factor of 11%. The exact values and timing of the observed dynamics may be affected by uncertainty, but the basic implications for the results remain valid.

7.3 Results

Assuming the dynamics of the activity flows taken from the activity model instead of the ‘flat’ estimations originally made in the energy model has a direct and significant impact on the results of the energy model. The results in this study are different in magnitude from those discussed in chapter 5, of course. But also the relative increase and decrease with respect to the reference year 2005 are different. The combination of higher demolition and lower construction activities makes the stock grow at a lower pace. Hence, also energy demand will grow at a lower pace. Higher levels of both renovation and demolition will reduce the inertia of the system, and changes will happen more rapidly. A higher renovation activity means that any policy effect due to renovation will be stronger than the effect due to new construction.

The past and projected delivered energy demand is presented in Figure 7.2, and a summary of the scenario analysis results is given in Table 7.1

Table 7.1 Delivered energy for all the scenarios for the Mid-Norway residential sector. Totals and grouped by different criteria.

Delivered Energy by year 2035 [TWh/y]

Scenario	Total	Electricity	Thermal carriers	Stock unchanged	Renovation	New
Reference year 2005	5.0	3.8	1.2			
Base	5.4	3.9	1.5	2.6	1.7	1.1
Thermal	5.7	3.2	2.6	2.6	1.9	1.2
Heat Pump	4.8	4.0	0.8	2.6	1.3	0.9
Base + Conservation	3.9	2.9	1.0	2.6	0.8	0.5
Thermal + Conservation	4.1	2.7	1.4	2.6	0.9	0.5
Heat Pump + Conservation	3.8	2.9	0.8	2.6	0.7	0.4

Figure 7.3 compares the results from all scenarios as in year 2035; the situation in the reference year 2005 is also reported for comparison[6]. The total is subdivided into electricity and the sum of thermal carriers. The percentage reported inside the grey bars is the percentage of electricity share.

Concerning the scenarios without conservation measures, the relative increase from year 2005 is limited – or there is even an actual decrease in the heat pump scenario – when compared to the outcomes in chapter 5. As noticed, this is the effect of a lower pace of growth in the stock. The consideration that policies for thermal carriers or heat pumps produce conflicting outcomes remains valid. On one hand it is possible to reduce electricity dependency at the price of higher total consumption; on the other hand it is possible to limit the total consumption at the price of increasing electricity dependency.

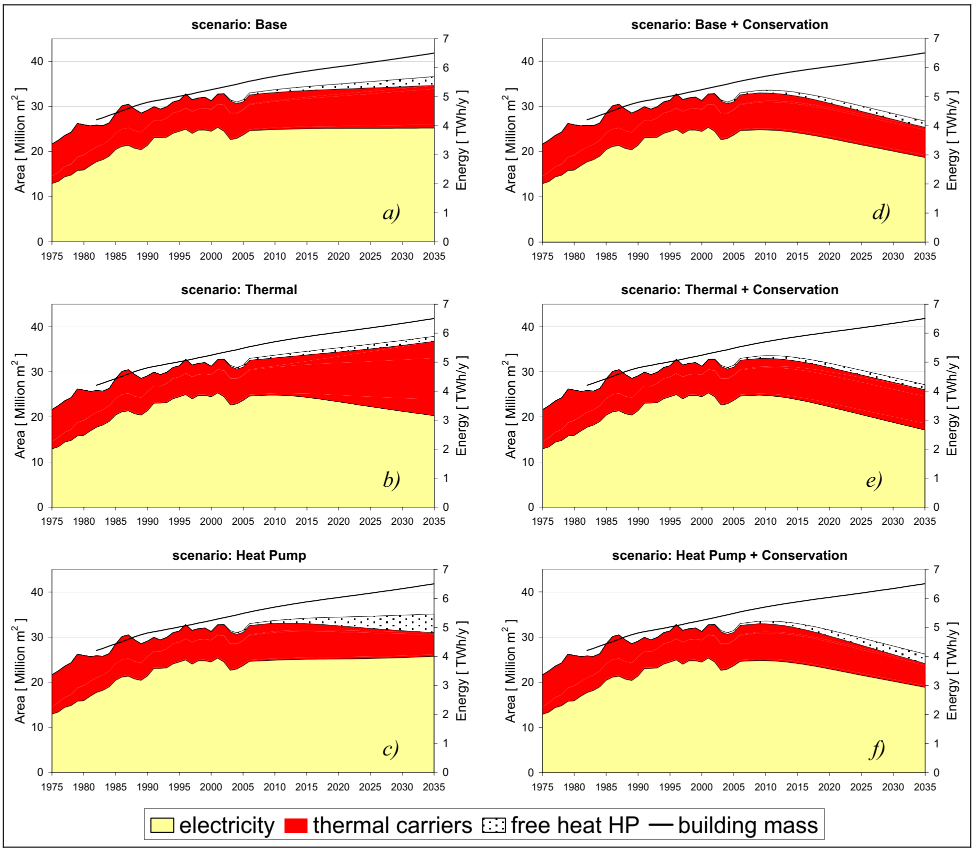

Figure 7.2 **Delivered energy results for the different scenarios for the Mid-Norway residential sector. On the left side: *a)* Base, *b)* Thermal and *c)* Heat Pump. On the right side the same scenarios plus energy conservation measures: *d)*, *e)* and *f)* respectively.**

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[6] the reference year 2005 has the actual stock of year 2005 but energy class and user preference defined as the trend value of the observation period 1996-2005.

Concerning the scenarios with conservation measures, the relative decrease from year 2005 is amplified when compared to the outcomes in chapter 5. This is the combined effect of having a slow growing stock and a smaller inertia in the system, as noticed. In chapter 5 it was seen that while the building stock grows 26% larger the energy demand is expected to become 14-20% smaller. In the sole residential sector in Mid-Norway the situation is that of a building stock growing 19% larger while the energy demand is expected to become 20-26% smaller (electricity being reduced by 23-30%). Other smaller differences are due to the fact that only the residential sector is considered. For example, in the residential sector wood is the most used thermal carrier, and it has the worst efficiency (see Table A2 in Appendix A of chapter 5). Therefore, when shifting the user preference from the trend values toward heat pumps, the benefit is greater in the residential sector than in the service sector.

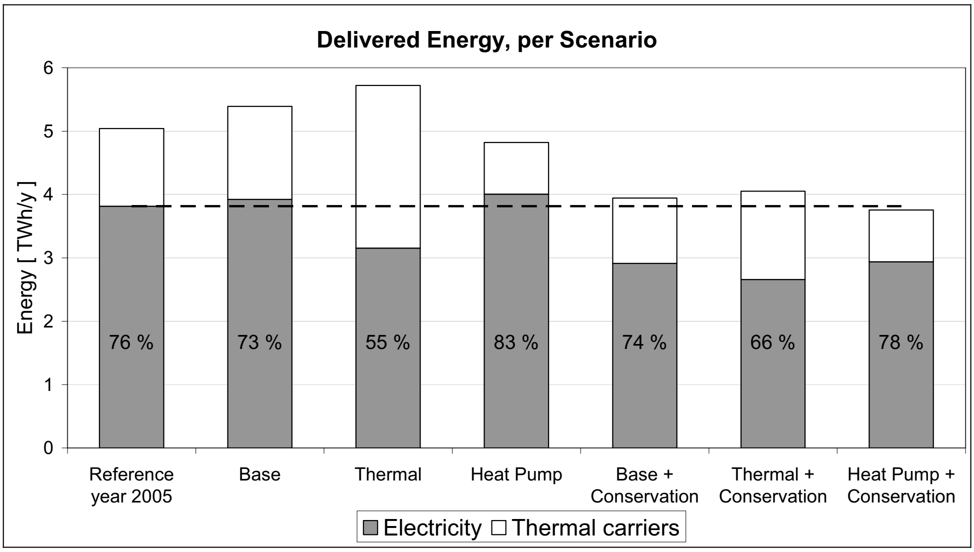

Figure 7.3 **Total delivered energy by 2035 for each scenario for the Mid-Norway residential sector, divided into electricity and sum of thermal carriers.**

In absolute terms, the adoption of conservation measures, i.e. construction of passive house and energy efficient renovation of existing houses, reduces considerably both the electricity demand and the total energy demand. The electricity demand can be reduced between 0.9 and 1.1 TWh/y, while total delivered energy can be reduced between 0.9 and 1.2 TWh/y with respect to the 2005 reference values. The primary goal in the Mid-Norway region may be that of reducing electricity demand to a minimum, in order to free this resource for other uses, such as expansion of energy intensive industrial activities in the same area. From this point of view the most convenient policy is given by the combination of conservation measures and substitution of electricity with thermal carriers for heating purposes. This case is represented by the scenario Thermal carriers + Conservation measures, where the electricity demand is reduced by 1.1 TWh/y. This achievement is only partly counterbalanced by an increase in the demand for thermal carriers of 0.2 TWh/y.

The results in Figure 7.4 confirm what has already been mentioned, that renovation is more influential than new construction in determining the effect of a policy. This outcome is different from the one in chapter 5, where the two activities were more or less equally influential. The hypotheses on the policies are the same, though, on both energy class and user preference options. The major difference is in the estimated activity flows: the renovation activity is here supposed to be higher than new construction, while in chapter 5 the two were assumed equal.

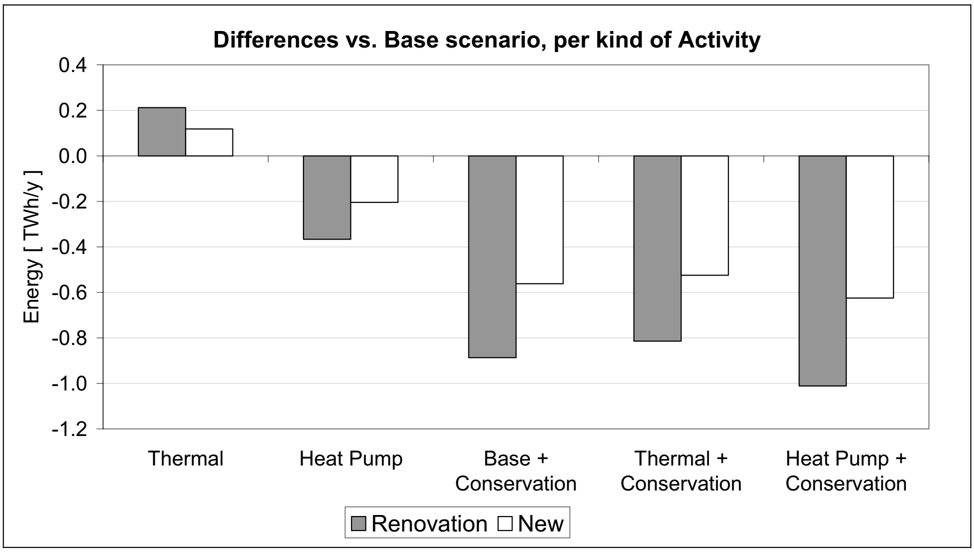

Figure 7.4 **Differences in energy consumption compared to the Base scenario by 2035, for the Mid-Norway residential sector, divided into renovation and new construction.**

The difference in the activity levels is the major cause of the different results. A minor contribution is also given by the fact that here only the residential sector is considered. In the energy model new construction in the residential sector is already in class D by default, while it is in class E in the service sector – these settings being the consequence of observations made on the available intensity data. The final target is a passive house standard (class A+) for both sectors, with the consequence that the improvement is smaller for the residential sector than it is for the service sector.

7.4 Conclusions

The results show that in the Mid-Norway region there is the potential, by the year 2035, to reduce the total energy demand by 20-26% and the electricity demand by 23-30% compared with year 2005 values. This is achieved despite the fact the residential stock grows one fifth larger. These achievements are possible when combining two actions. One action is to build all new buildings with a passive house standard (class A+) from 2015 onward, allowing a gradual improvement from today's average to the 2015 goal. The second action is to improve the energy performance of all renovated buildings to class A from 2020 onward, allowing a gradual improvement from today's average to the 2020 goal. If the main goal in the Mid-Norway region is that of reducing electricity demand to a minimum, then the most convenient policy is to promote passive house technologies in combination with substitution of electricity with thermal carriers for heating purposes. This would have the potential of reducing electricity demand by 1.1 TWh/y, from the 3.8 TWh/y in year 2005 down to the 2.7 TWh/y in year 2035. Depending also on the measures taken in the service sector and the industry, the promotion of passive houses will contribute to limit or even totally eliminate the necessity to increase power production and the grid capacity in the Mid-Norway region.

Regarding the methodology, this study explores integrating the estimations on the stock dynamics into the energy policy analysis. This means merging the model presented in chapter 5 (the energy model) and the model presented in chapter 6 (the activity model). Considering the dynamics of activity flows such as new construction, renovation and demolition proved to have a great impact in determining the potential of the energy policies.

8 Conclusions and future work

This chapter briefly summarizes the findings of each article and gives an overall view of the results of this thesis work.

8.1 PART I – case studies

Chapter 2: Energy use in the life cycle of conventional and low-energy buildings: A review article

The purpose of chapter 2 was to study the relation between the embodied energy and the operating energy, and how this varies in conventional and low-energy buildings. The literature reviewed showed that operating energy represents by far the largest part of total energy demand. It was shown that at parity of all other conditions, the design of low-energy buildings induces a net benefit in total life cycle energy, in the order of two to four times lower, even though the embodied energy results somewhat increased.

Based on these outcomes the rest of the thesis work has focused on the potential for reducing the operating energy demand. In the following case study this potential has been investigated for the renovation of a non-residential building.

Chapter 3: Calibration of multiple energy simulations: case study on a Norwegian school building

The purpose of chapter 3 was to investigate how a Monte Carlo method could improve the manual calibration process and generate a set of multiple calibrated solutions. The Monte Carlo method proved able to: identify a set of calibrated solutions that match predefined criteria, improve the overall goodness of a manually calibrated solution, and provide insights on the most influential parameters. The experience gained suggested that combining the Monte Carlo method with a manually semi-calibrated model would optimise time and results of the calibration process.

The calibrated model of the school was used in the work presented in chapter 4.

Chapter 4: Case study on retrofit of a Norwegian school: possible to achieve the passive house standard?

The purpose of chapter 4 was to use building energy simulations for studying the possibility to achieve the passive house standard through a series of retrofit measures. The simulations included improvements in: controls, lighting, ventilation, windows and insulation. The results showed that it is possible to achieve high levels of energy efficiency, i.e. class A or the passive house standard, when the envelope properties (windows and insulation) are significantly improved. Also the design of the ventilation system has to be properly sized, in order to avoid unnecessary high flow rates, as that would cause higher energy demand.

The experience gained with the case studies investigated in PART I provided useful insights for developing the content of PART II. In particular, it has been important to have a clear awareness that significant improvements in the energy performance of an existing building can be obtained only through major renovation work. The consequence is that the stock will have a certain inertia to changing its energy demand, and that this inertia to a large extent will be independent of any energy policy.

8.2 PART II – scenario analysis

Chapter 5: Modelling energy demand in the Norwegian building stock: scenario analysis based on activity flows, energy class and user preference

The purpose of chapter 5 was to study the effect of three hypothetical policies, and combinations of them, aimed at maximising the diffusion of thermal carriers, heat pumps, and conservation measures respectively. A model was developed with a demand side perspective. The results showed the robustness of policies that included conservation measures against the conflicting effects of the other polices. Adopting conservation measures on a large scale has the potential to reduce both electricity and total energy demand from present day levels while the building stock keeps growing. The results also highlighted the inertia to change of the building stock, and the importance of making a clear distinction between the assumptions on intensity and activity levels has been discussed.

Modelling energy demand made it clear that it is of utmost importance to improve the understanding of the stock dynamics that determine the building activities. That has been the content of the next article. Nevertheless, this was possible only for the residential stock.

Chapter 6: Toward modelling of construction, renovation and demolition activities: Norway's dwelling stock 1900-2100

The purpose of chapter 6 was to gain insights into the possible evolution of the dwelling stock and related activities in the future. A model was developed based on a dynamic material flow analysis. The results showed that in all scenarios analysed the construction activity is expected to slow down in the coming decades while renovation is expected to increase. This may be a temporary phenomenon, but it is likely that in the next decades renovation will overtake construction as the major building activity in the Norwegian residential sector.

In the next chapter an attempt was made to merge the two models developed in chapters 5 and 6.

Chapter 7: Mid-Norway as a pilot region for promotion of passive houses: A study of the potential

The purpose of chapter 7 was to estimate the potential for energy and electricity savings in the residential sector in the Mid-Norway region. The results showed that by implementing energy conservation measures the potential is to reduce total energy demand by 20-26% and electricity demand by 23-30% by year 2035 compared to 2005 values. This is achieved despite the fact that the residential stock grows 19% larger. Depending also on the measures taken in the service sector and the industry, the promotion of passive houses will contribute limiting or even totally eliminate the necessity to increase power production and the grid capacity in the Mid-Norway region.

8.3 Overall considerations

The work performed in the first part of this thesis on development and survey of case studies provided background knowledge that was then used in the second part. Modelling of energy demand in the Norwegian building stock was developed with due consideration to the lessons learnt in the case studies analysis. It became clear that the scarcity of available information on building activities made it not suitable to the purpose of energy modelling, and a deeper understanding of the stock dynamics was needed as a precondition for addressing energy demand in a more consistent way. Further investigation on the subject led to explore, though only for the residential sector, a methodology for assessing both stock and flows of floor area in a coherent way. Finally, the two developed models, the energy model and the activity model, were merged to perform an integrated analysis of the energy demand at a regional level. The result showed how considering the stock dynamics have a great impact in determining the effectiveness of a policy.

The scenario analysis on energy demand in the building stock, both at the national level and at the regional level for the Mid-Norway residential sector, showed that adopting conservation measures on a large scale has the potential to reduce both electricity and total energy demand from present day levels while the building stock keeps growing. Nonetheless, the results also showed the inertia to change in the building stock, due to low activity levels compared to the stock size. Such considerations – great potential and long term effect – may be used to invoke that the building stock should be regarded as being an energy infrastructure itself, and energy policies should aim at maximising its efficiency. This perspective on the building stock may help avoiding the risk of a permanent lock-in, where the choice between supply and demand strategies always would favour substitution of fuels or increased energy production at the expense of energy efficiency.

8.4 Future work

The work presented in this thesis can be improved and expanded. Suggestions on directions where to address future work are already partly discussed in the conclusions of each article. This paragraph summarises those suggestions and tries to develop them a bit further, in a more comprehensive view.

The quality of data on building activities should be improved. The scarcity of data available was indeed a motivation to develop a model to study the dynamics in the residential stock. A similar approach could be adopted also for the stock of non-residential buildings. However, modelling the service sector stock would require careful consideration of relevant parameters to represent the drivers in the demand for non-residential floor area. The drivers and the parameters might be very different from those included in the analysis of the residential building stock.

The quality of data on energy intensity can also be improved, especially for what concerns renovation and the service sector. In order to do so, it is possible to imagine undertaking a series of case studies as the one presented in chapters 3 and 4. One possibility may be, for example, to do this on some of the buildings whose energy consumption is well monitored within the building network program of the Enova agency. In parallel, more information may become available thanks to the introduction of the energy certificates, with the enforcement of the EPBD.

A further level of detailing may be considered in the definition of the archetypes that describe the building stock. This may include subdivisions based on climatic zones, type of area (urban/rural, high/low energy density), disaggregation of building sectors into categories, age groups and types of heating system available. Also, other renewable energy sources may be considered, i.e. solar thermal and photovoltaic systems. Nevertheless, it shall be considered that, apart from the difficulties in resourcing the necessary information, the number of archetypes would grow rapidly, and the potential benefit coming from a more detailed description of the stock should be weighted against the increasing complexity of the model.

In this thesis work no economic analysis was undertaken. There is no doubt that a cost/benefit analysis of any measure or policy is extremely important. A proper economic evaluation, though, should be made with a holistic approach to the energy system. Demand and supply strategies should be evaluated alongside each other, in order to assess the overall costs and benefits for the entire society. Furthermore, the entire analysis would be heavily dependent on the development of energy prices and the prices of carbon emission permits. Such an analysis was beyond the scope of this thesis.

However, it would be possible to extend the energy model in order to perform at least an analysis of the investment cost associated to the different measures. Once again, it is possible to imagine undertaking a series of case studies as the one presented in chapters 3 and 4, including also estimation of the investment cost. Then, it would be possible to scale up the investment cost analysis from the single cases to the entire stock, in a similar fashion as done with energy.

Extending the boundaries of the energy model from delivered to primary energy for allowing estimation of CO_2 emissions may also be considered. As a first approach, this could be done by means of national or European average conversion factors and emission coefficients per each energy carrier.

When all the three indicators: energy consumption, CO_2 emissions and investment cost are available, then this information could be given as input to an economic model. This would allow performing a more comprehensive economic analysis that considers also energy prices and prices of carbon emission permits.

An interesting alternative would be to integrate demand and supply side models. Supply side models can, to a certain extent, internalize energy prices and carbon emission permit prices, but usually assume energy demand as an exogenous variable, often being the simple trend continuation of past values (see for example the Markal model developed in the TRANSES project, ref. Acknowledgements). Estimations made by demand side models like the one presented in this thesis would provide better guesses.

Furthermore, combining the analysis of energy demand in the building stock with similar analyses in the industry and transport sectors, would ultimately enable harmonized planning of energy demand and supply strategies. This would improve the decision makers’ capability of managing current issues of utmost importance, such as greenhouse gases emission and scarcity of resources, which hinge upon energy production and consumption issues.

Appendix A

Midt-Norge som pilotregion for passivhus satsing: Potensialstudie

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Sammendrag

Ifølge Statnett er de største utfordringene for utviklingen av det sentrale kraftnettet i Norge i dag knyttet til at det forventes betydelig forbruksøkning i Midt-Norge, samtidig som det er stor usikkerhet knyttet til eventuell ny produksjon i området. Faktorer som bidrar til at forbruket øker er høy aktivitet i bygningssektoren og flere nye industriprosjekter i regionen. Dersom forbruksøkningen blir som forventet vil dette nødvendiggjøre kostnadskrevende tiltak på forsyningssiden. Det er derfor spesielt interessant å undersøke regionale tiltak som kan bidra til at forbruksøkning begrenses eller unngås.

I denne artikkelen er det gjennomført en analyse for å undersøke i hvor stor grad en storstilt satsing på passivhus og energieffektiv rehabilitering av eksisterende boliger i Midt-Norge vil redusere det forventede kraftforbruket. Følgende scenarier frem mot år 2035 er beregnet: *”Basis”, ”Energidirektivet”, ”Passivhus satsing”, ”Overgang til termiske energibærere”, ” Passivhus satsing + termiske energibærere”, ”Satsing på varmepumper”* og *”Passivhus satsing + varmepumper”.*

Resultatene for de ulike scenarier viser store variasjoner i forventet forbruk av elektrisitet og termiske energibærere i boligsektoren i Midt-Norge. Av de enkeltstående tiltak vurdert i denne studien er det passivhus satsingen som vil gi størst effekt både når det gjelder reduksjon av elektrisitetsforbruk og forbruk av termiske energibærere i Midt-Norsk boligmasse. Overgang til mer bruk av termiske energibærere til oppvarming vil også bidra betydelige reduksjoner i elektrisitetsforbruket, men vil samtidig øke det totale energiforbruket. Økningen skyldes dårligere virkningsgrad for oppvarmingssystemene en ved direkte bruk av elektrisitet.

Gjennom å kombinere satsingen på passivhus teknologi med bruk av andre energibærere enn elektrisitet til oppvarming er det beregnet at elektrisitetsforbruket i Midt-Norske boliger vil reduseres fra 3,75 TWh i år 2000 til 2,74 TWh i år 2035. Dette utgjør en reduksjon på ca. 1 TWh eller 27 %. Avhengig av hva som gjøres i forhold til næringsbygg, og utviklingen i industri, transport og energisektoren, kan dette bidra til å eliminere behovet for ny kraftproduksjon i Midt-Norge og forsterkning av overføringskapasitet inn til regionen i uoverskuelig fremtid. Strategier for å bedre energiytelsen til boligsektoren bør derfor inngå som en av flere viktige elementer i Midt-Norges fremtidige energi- og miljøpolitikk.

Introduksjon

Ifølge Statnett er de største utfordringene for utviklingen av det sentrale kraftnettet i Norge i dag knyttet til betydelig forbruksøkning i Midt-Norge, samtidig som det er stor usikkerhet knyttet til eventuell ny produksjon i området. Dette vil nødvendiggjøre store investeringer på forsyningssiden. Alle tiltak som kan begrense forbruksveksten vil kunne bidra til å begrense behovet for forsterkning av overføringskapasitet og etablering av ny kraftproduksjon.

Av hensyn til miljø og samfunnsøkonomi er det er derfor spesielt interessant å se på tiltak som kan begrense forbruksveksten i Midt-Norge. Denne artikkelen tar for seg potensialet for å redusere veksten i elektrisitetsforbruk og øvrig energiforbruk i Midt-Norge i forbindelse med nybygging og rehabilitering av boligene i regionen. Konsekvensene av satsing på passivhus teknologi og alternativer til elektrisitet som oppvarmingskilde er analysert spesielt.

Metode

Historisk forbruk av energivarer og aktiviteter (areal, produsert enhet e.l.) kan benyttes til å trendfremskrive den videre utvikling og på denne måten etablere et basisscenario, som igjen gir grunnlag for å vurdere andre alternative scenario.

Energibruken for de forskjellige energibærerne E_i kan uttrykkes som produktet av aktivitet (A_i) og intensitet (I_i):

$$E_i = A_i \cdot I_{ij} \tag{1}$$

der aktiviteten A_i er definert som antall m^2 bruksareal (BRA) for bygningstype i, mens intensiteten I_{ij} er definert som årlig mengde levert energi per m^2 BRA for bygningstype i og energikilde j [kWh/m$^{2}\cdot$år].

Boligmassen

Her representerer parameteren A i ligning (1) boligmassen, inkludert fritidsboliger. Den historiske utviklingen av den Norske boligmassen er tidligere analysert i forbindelse med utvikling av et nasjonalt planleggingsverktøy for energiplanlegging [1]. Flere datakilder ble analysert i forbindelse med dette arbeidet [2,3,4,5].

Den historiske utviklingen av boligmassen i Midt-Norge er ikke analysert i detalj, men analyse av data fra GAB-registeret [5] viser at brutto areal av boligmassen i region Midt-Norge (Møre og Romsdal, Sør-Trøndelag og Nord-Trøndelag) i år 2005 utgjorde 11 % av boligmassens totale brutto areal i Norge. I analysene gjennomført her er det antatt at utviklingen av boligmassen i Midt-Norge etter år 2005 vil følge utviklingen i resten av landet.

Energiintensitet for en gjennomsnittsbolig

Referansenivå for *energiintensitet per bruksareal, I,* for eksisterende leiligheter og småhus er hentet fra en utredning av energimerkeordning for boliger i Norge [6]. Energiintensitet per bruksareal for fritidsboliger er hentet fra en tidligere analyse [7].

Behovet for levert energi til en eksisterende gjennomsnittsbolig fremkommer ved å vekte disse verdiene i forhold til deres respektive andel av boligmassen.

Når det gjelder nybygg er det i forbindelse med innførsel av energidirektivet i Norge gjennomført en revisjon av Teknisk forskrift til byggverk og produkter (TEK 97- Rev. 2007). Det er i den forbindelse etablert en ny metode for beregning av bygningers energiytelse. Metoden er dokumentert gjennom en ny norsk standard, NS3031:2007 [8]. I den reviderte forskriften er det etablert *energirammer* som angir maksimalt tillatte netto energibehov for den aktuelle bygningstypen, beregnet etter NS3031:2007. I forbindelse med fastsettelse av energirammene er det gjennomført beregninger for typiske nye leiligheter og småhus som akkurat tilfredsstiller minimumskravene [9]. Netto spesifikt energibehov for et gjennomsnittlig ny bolig fremkommer, på samme måte som behovet for levert energi til en eksisterende gjennomsnittsbolig, ved å vekte resultatene fra disse beregningene i forhold til bygningstypenes respektive andel av boligmassen.

Tabell 1 **Beregnet energibudsjett for en ny og eksisterende gjennomsnittsbolig. Tallene er per oppvarmet del av bruksareal.**

Energibudsjett - gjennomsnittsbolig	**Eksisterende** spesifikt behov for levert energi [kWh/m2/år]	Andel av total [%]	**Ny** spesifikt netto energibehov [kWh/m2/år]	Andel av total [%]
1a Romoppvarming	135	63 %	37	30 %
1b Ventilasjonsvarme	0	0 %	6	5 %
2 Varmt vann	37	18 %	30	25 %
3 Vifter og pumper	1	0 %	8	7 %
4 Belysning	17	8 %	17	14 %
5 Teknisk utstyr	23	11 %	23	19 %
6 Kjøling	0	0 %	0	0 %
Totalt	213	100 %	121	100 %

Det resulterende behovet for levert energi til en eksisterende gjennomsnittsbolig, og netto energibehov for en ny gjennomsnittsbolig, er vist i Tabell 1. Merk at vi også har tatt hensyn til boligmassen av fritidsboliger i disse beregningene.

Energistatistikk

Data for stasjonært forbruk av energivarer for private husholdninger er gitt av energiregnskapet til SSB [10]. Statistikken gir tall på forbruket av hver enkelt energikilde.

Ved å dividere det totale forbruket på *brutto areal* av boligmassen fås *tilført energi per brutto areal* for en gjennomsnittsbolig. Denne energiintensiteten varierer noe fra år til år avhengig av en rekke parametere. Gjennomsnittlig energiintensitet i perioden 1996-2005 er beregnet til 146 kWh/m$^{2\cdot}$år.

Dette gir en omregningsfaktor fra energiintensitet per oppvarmet bruksareal (se Tabell 1) til energiintensitet per brutto areal 146/213=0,69.

Sluttbrukerpreferanse for energikilde til oppvarming

Sluttbrukerpreferansen for energikilde til oppvarming er definert som andelen av de forskjellige energikilder som benyttes til å dekke varmebehovet, det vil si behovet for romoppvarming, oppvarming av ventilasjonsluft og tappevann. Denne preferansen vil endre seg over tid som funksjon av hvor stor andel av netto behov oppvarmingen til enhver tid utgjør, og trendutviklingen for bruk av de forskjellige energikilder. Vi har her valgt å beregne fremtidig sluttbrukerpreferanse for energibruk til oppvarming som en lineær trend basert på utviklingen fra 1996-2005, se Tabell 2. Andelen elektrisitet beregnes som det gjenværende, som betyr at trendutviklingen for elektrisitet også er helt lineær inntil all bruk av fyringsoljer i boliger er utfaset i 2034.

Tabell 2 **Gjennomsnittlig sluttbrukerpreferanse for energikilde til oppvarming for periode 1996-2005, og beregnet sluttbrukerpreferanse i år 2035.**

År	**Direkte bruk av elektrisitet**	**Fjernvarme**	**Ved**	**Gass**	**Olje**	**Varme fra varmepumper**
2000 (1996-2005)	80,7 %	0,9 %	8,9 %	0,3 %	8,1 %	1,1 %
2035	61,8 %	2,7 %	18,7 %	2,5 %	0,0 %	14,4 %

Definisjon av arketyper

Dersom resultatene av alternative scenario skal gi nyttig informasjon bør de komme som en direkte konsekvens av reelle valg og strategier. Vi har her valgt å ta utgangspunkt i foreliggende forslag til energimerkesystem for norske boliger [6] og benyttet det foreslåtte klassifiseringssystem som utgangspunkt såkalte arketyper. En arketype er et typebygg ment å representere en del av bygningsmassen. Arketypene gjør det lettere å systematisere antagelsene og hypotesene rundt bygningsmassens utvikling for de forskjellige scenario som ønskes analysert.

For hver energiklasse definert i Tabell 3 er det definert egne arketyper. Arketypene inneholder både netto energibehov og behovet for levert energi. Koblingen mellom netto og levert energi utgjøres av *sluttbrukerpreferansen av energikilde til oppvarming* og *systemvirkningsgraden*[7] for de aktuelle energisystem.

Tabell 3 **Foreslått kravnivå for Norsk energimerkeordning [6**Error! Bookmark not defined.**].**
Rr (Eng: Reference regulation)=Maksimalt tillatt netto energibehov gitt i TEK 97 – Rev. 07.
Rs (Eng: Reference stock)=Behov for levert energi til en gjennomsnittsbolig.

Klasse	Kravnivå
A+	≤ 0.25 · Rr
A	≤ 0.5 · Rr
B	≤ 0.75 · Rr
C	≤ Rr
D	≤ 0.5 · (Rr + Rs)
E	≤ · Rs
F	≤ 1.5 · Rs
G	> 1.5 · Rs

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[7] Systemvirkningsgraden er gitt av produktet av produksjonsvirkningsgraden, distribusjonsvirkningsgraden og reglueringsvirkningsgraden, $\eta_{system=}\eta_{produksjon}\cdot\eta_{distribusjon}\cdot\eta_{regulering}$

Systemvirkningsgradene er hentet fra tabell B.9 og B.10 i NS3031:2007 med ett unntak: Når det gjelder vedovner angir NS3031:2007 en systemvirkningsgrad på 0,64 både for gamle og nye ovner. En systemvirkningsgrad på 0,64 forutsetter imidlertid en rentbrennende ovn, og ifølge SSB ble bare 20 % av veden brent i slike ovner i 2002 [11]. For åpne ildsteder eller eldre vedovner som fyres med redusert lufttilførsel kan en anta en produksjonsvirkningsgrad på 0,4. Med en reguleringsvirkningsgrad på 0,8 gir dette en systemvirkningsgrad på 0,36. Med dette som utgangspunkt er gjennomsnittlig systemvirkningsgrad i eksisterende boliger i år 2000 anslått til 0,42. Systemvirkningsgradene benyttet i analysene er gitt i Tabell 4. Arketypenes struktur er illustrert i for arketypen slik illustrert i Tabell 5.

Tabell 4 Systemvirkningsgrader benyttet i analysene.

direkte bruk av elektrisitet	oppvarming					
	olje	gass	ved	fjernvarme	elektrisitet	varme fra varmepumpe
1.00	0.72/0.77[a]	0.77 / 0.81[a]	0.42 / 0.64[a]	0.86/0.88[a]	1.00	2.16

[a] Verdien til venstre representerer oppvarmingssystemer eldre enn 1990, og er anvendt for eksisterende bygninger, mens verdien til høyre representerer nye oppvarmingssystemer, og er anvendt for rehabiliterte eller nye bygninger

Tabell 5 Strukturen til arketypene.

Arketype *XY*: Energiklasse *X*, Sluttbrukerpreferanse *Y* for energikilde til oppvarming				
Netto energi			**Levert energi**	
netto behov	[kWh/m^{2}år]		energibærer	[kWh/m^{2}år]
total Netto			**total Levert**	
elspesifikt behov	*x1*	*"➔ sluttbrukerpreferanse for energikilde til oppvarming og systemvirkningsgrad for oppvarmings/kjølesystem ➔"*	elektrisitet	*y1*
kjøling	*x2*		fjernvarme	*y2*
varme	*x3*		ved	*y3*
			gass	*y4*
			olje	*y5*
			omgivelsesvarme via varmepumpe	*(y0)*
Avhenger av energiklasse			*Avhenger av systemvirkningsgrad og sluttbrukerpreferanse*	

I tillegg til at hver energiklasse har sine arketyper er det definert egne arketyper for startåret (år 2000) og sluttåret (år 2035) for analysene. Forskjellen mellom startåret og sluttåret er at *sluttbrukerpreferansen for energikilden til oppvarming* og *systemvirkningsgraden* for oppvarmingssystemene har endret seg slik det fremgår av henholdsvis Tabell 2 og Tabell 4. Figur 1 viser arketypene som representerer en gjennomsnittsbolig (*Energiklasse E = Rs – se* Tabell 3) i henholdsvis år 2000 (øverst) og år 2035 (nederst). Som vi ser er netto tallene like for de to arketypene ettersom de representerer samme energiklasse, mens tallene for levert energi er forskjellige som følge av forskjellig sluttbrukerpreferanse for energikilde til oppvarming (se Tabell 2) og systemvirkningsgrad (se Tabell 4). Legg også merke til at tallene for gjennomsnittsboligen anno år 2000 stemmer overens med tallene i Tabell 1.

Med utgangspunkt dataene fra Tabell 1, Tabell 2 og Tabell 3 er det etablert tilsvarende arketyper for de øvrige energiklasser for år 2000 og år 2035.

Energiklasse E (Rs) år 2000											
netto energi							**levert energi**				
energibehov	kWh/m2/år	andel	energibærer	sluttbruker-preferanse	kWh/m2år	system-virkningsgrad	energibærer	kWh/m2/år	energibærer	kWh/m2/år	andel
	190,0									213,0	
elspesifikt	**41,0**	21,6 %				1,00	elektrisitet	41,0	elektrisitet	162,1	76,1 %
kjøling	**0,0**	0,0 %				1,40	elektrisitet	0,0			
oppvarming	**149,0**	78,4 %	direkte bruk av elektrisitet	80,7 %	120,3	1,00	direkte bruk av elektrisitet	120,3			
			fjernvarme	0,9 %	1,4	0,86	fjernvarme	1,6	fjernvarme	1,6	0,7 %
			ved	9,3 %	13,9	0,42	ved	33,1	ved	33,1	15,5 %
			gass	0,3 %	0,4	0,77	gass	0,6	gass	0,6	0,3 %
			olje	7,6 %	11,3	0,72	olje	15,7	olje	15,7	7,4 %
			varme fra VP	1,1 %	1,7	2,16	elektrisitet til drift av VP	0,8			
							omgivelses-varme via VP	0,9	omgivelses-varme via VP	0,9	---

Energiklasse E (Rs) år 2035											
netto energi							**levert energi**				
energibehov	kWh/m2/år	andel	energibærer	sluttbruker-preferanse	kWh/m2/år	system-virkningsgrad	energibærer	kWh/m2/år	energibærer	kWh/m2/år	andel
	190,0									196,2	
elspesifikt	**41,0**	21,6 %				1,00	elektrisitet	41,0	elektrisitet	142,0	72,4 %
kjøling	**0,0**	0,0 %				1,40	elektrisitet	0,0			
oppvarming	**149,0**	78,4 %	direkte bruk av elektrisitet	61,1 %	91,0	1,00	direkte bruk av elektrisitet	91,0			
			fjernvarme	2,6 %	3,9	0,88	fjernvarme	4,4	fjernvarme	4,4	2,3 %
			ved	19,5 %	29,1	0,64	ved	45,5	ved	45,5	23,2 %
			gass	2,3 %	3,5	0,81	gass	4,3	gass	4,3	2,2 %
			olje	0,0 %	0,0	0,77	olje	0,0	olje	0,0	0,0 %
			varme fra VP	14,4 %	21,5	2,16	elektrisitet til drift av VP	10,0			
							omgivelses-varme via VP	11,5	omgivelses-varme via VP	11,5	---

Figur 1 **Arketype for en gjennomsnittsbolig (*Energiklasse E*=Rs) i henholdsvis år 2000 (øverst) og år 2035 (nederst).**

Forutsetninger for energiscenariene

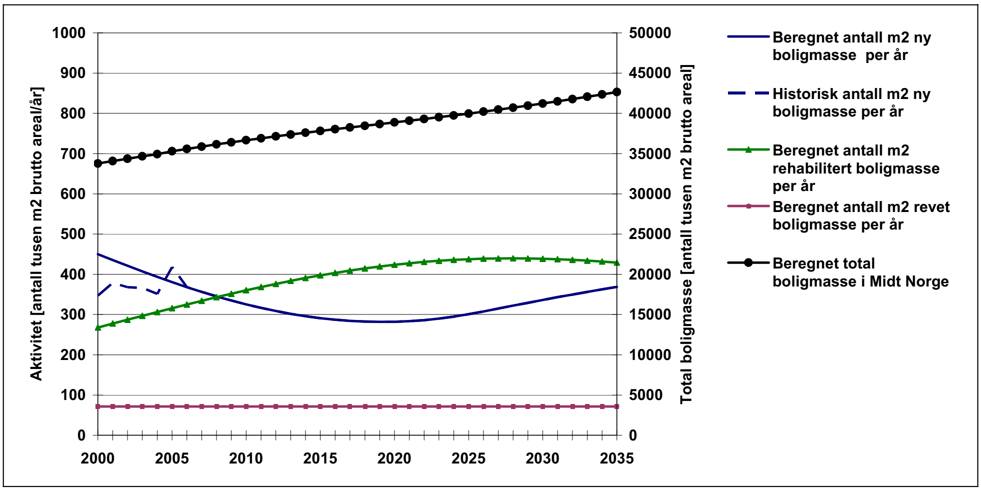
Hensikten med scenariene er primært å undersøke konsekvensene av en aktiv satsing på passivhus-teknologi, både for nye boliger og ved rehabilitering av eksisterende boliger. I alle scenarier forutsetter vi imidlertid at netto spesifikt energibehov ikke endres for eksisterende bygg som ikke rehabiliteres. Dette betyr at bygg som ikke rehabiliteres beholder samme energiklasse gjennom hele den analyserte perioden. Det eneste som endres for disse byggene er *sluttbrukerpreferansen for energikilde til oppvarming,* som gradvis nærmer seg 2035-nivå i henhold til Tabell 2. Dette betyr i praksis at andelen av varmebehovet som dekkes av ved, omgivelsesvarme via varmepumper, fjernvarme og gass gradvis øker for disse boligene, mens andelen olje og elektrisitet gradvis reduseres.

Aktivitet innen nybygg og rehabilitering

For å beregne aktivitet innen rivning, nybygg og rehabilitering er det utviklet en dynamisk metode som er anvendt på den norske boligmassen [12]. Vi har benyttet samme metode på boligmassen i Midt-Norge.

I [12] er det konstruert tre scenarier, et ”low” et ”medium” og et ”high”. Her har vi tatt utgangspunkt i input parameterne benyttet i ”medium”-scenariet. Dette innebærer en antatt gjennomsnittlig levetid for byggene på 100 år, et gjennomsnittlig rehabiliteringsintervall på 40 år, en lineær økning i folketallet frem mot år 2035 samt en utflating i antall personer per boenhet og antall m^2 bruksareal per boenhet.

Det resulterende aktivitetsnivå innen rehabilitering, nybygging og rivning, samt beregnet utvikling i total boligmasse i Midt-Norge er vist i Figur 2. Legg merke til at i motsetning til tidligere forventes antall rehabiliterte kvadratmeter boligareal overstige antall kvadratmeter nybygd areal de neste 30 år.



Figur 2 **På venstre akse er beregnet aktivitetsnivå i Midt-Norge angitt i antall tusen m^{2}brutto boligareal/år for henholdsvis nybygg (blå kurve), rehabilitering (grønn kurve) og rivning (plummefarget linje). På høyre akse er den totale boligmassen angitt i antall tusen m^{2}brutto areal (sort linje).**

Forutsetning med hensyn til energiklasse og sluttbrukerpreferanse

Med utgangspunkt i energiklassene definert i Tabell 3 gjelder følgende antagelser for alle scenarier:

- Eksisterende boliger som ikke rehabiliteres beholder energiklasse E i hele perioden, mens sluttbruker-preferansen for energikilde til oppvarming endres gradvis fra 2000-nivå til 2035 nivå i henhold til Tabell 2.
- Boliger som rives har samme energiklasse som eksisterende boliger som ikke rehabiliteres (energiklasse E) og den sluttbrukerpreferanse for energikilde til oppvarming som gjelder på rivningstidspunktet.
- Boliger som bygges fra år 2000 til år 2009 antas få energiklasse D mens sluttbrukerpreferanse for energikilde til oppvarming endres gradvis mot 2035 nivå i henhold til Tabell 2.
- Rehabilitering av eksisterende boliger fra år 2000 til år 2009 påvirker ikke boligenes energiklasse, mens sluttbrukerpreferansen for energikilde til oppvarming endres gradvis mot 2035 nivå i henhold til Tabell 2.

Det er så etablert seks scenarier med ulike forutsetninger:

Basis (business as usual)

Samme antagelser som over for hele perioden:

- Nybygg får energiklasse D
- Rehabilitering påvirker ikke energiklasse
- Sluttbrukerpreferansen for energikilde til oppvarming antas endres gradvis mot 2035 nivå i henhold til Tabell 2 både for uforandrede, rehabiliterte og nye bygg.

Energidirektivet

For dette scenariet antas de nye kravene i den reviderte TEK (TEK 97 – Rev. 2007) blir etterfulgt slik at:

- Alle nye boliger bygget i år 2010 eller senere får energiklasse C
- Rehabilitering medfører fra og med år 2010 en oppgradering fra energiklasse E til energiklasse D.
- Samme antagelse som for basis scenariet med hensyn til sluttbrukerpreferansen for energikilde til oppvarming.

Passivhus satsing

- Nybygg forbedres gradvis fra klasse C i 2010 til klasse A+ i år 2015.
- Rehabilitering medfører også en gradvis forbedring fra energiklasse D i år 2010 til energiklasse A i år 2020.
- Samme antagelse som for basis scenariet med hensyn til sluttbrukerpreferansen for energikilde til oppvarming.

Overgang til termiske energibærere

- Samme forutsetninger som basis scenariet med hensyn til energiklasse
- Sluttbrukerpreferansen for energikilde til oppvarming følger samme utvikling som for basis scenariet frem til år 2010. Fra år 2010 skjer det en gradvis overgang til en situasjon der sluttbrukerpreferansen for bruk av elektrisitet til oppvarming i 2035 er redusert til 25 % for alle nye og rehabiliterte boliger. For beregning av en gjennomsnittlig systemvirkningsgrad for de termiske energibærerne er det antatt at øvrig oppvarming dekkes med en like stor andel gass, fjernvarme og ved.

Satsing på varmepumper

- Samme forutsetninger som basis scenariet med hensyn til energiklasse
- Sluttbrukerpreferansen for energikilde til oppvarming følger samme utvikling som for basis scenariet frem til år 2010. Fra år 2010 skjer det en gradvis overgang til en situasjon der varmen fra varmepumper dekker 50 % av det totale oppvarmingsbehovet i rehabiliterte og nye boliger i år 2035.

Passivhus satsing + termiske energibærere

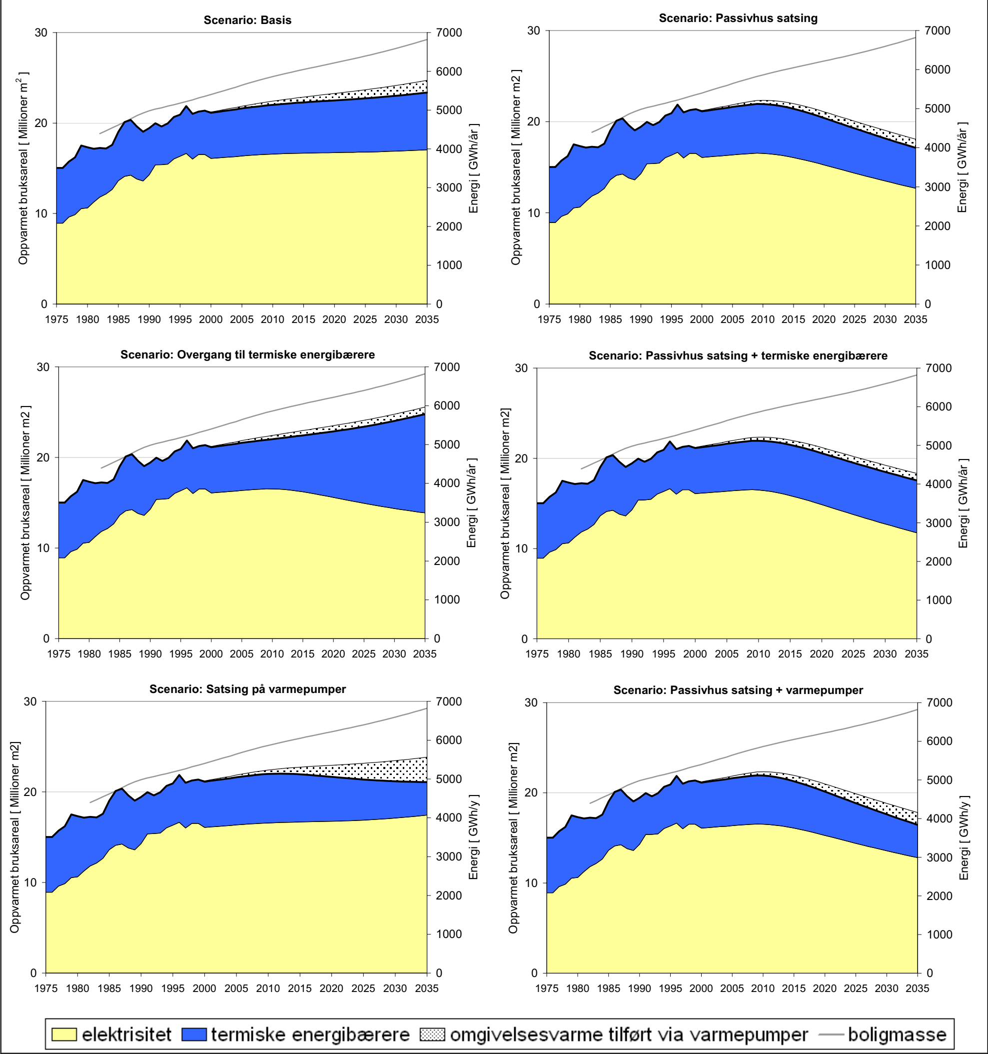
- Samme forutsetninger med hensyn til energiklasse som scenario "Passivhus satsing"
- Samme forutsetninger med hensyn til sluttbrukerpreferanse for energikilde til oppvarming som scenario "Overgang til termiske energibærere".

Passivhus satsing + varmepumper

- Samme forutsetninger med hensyn til energiklasse sm scenario “Passivhus-satsing”
- Samme forutsetninger med hensyn til sluttbrukerpreferanse for energikilde til oppvarming som scenario “Satsing på varmepumper”

Resultater

Figur 3 gir en oversikt over historisk forbruk og beregnet fremtidig levert energi til boligene i Midt-Norge for de forskjellige scenario. Total levert energi er summen av levert elektrisitet i gult og termiske energibærere i blått. Beregnet omgivelsesvarme tilført via varmepumper er også vist. Denne “gratisvarmen” er ikke inkludert i levert energi, men kommer som et tillegg. Resultatene er oppsummert i Tabell 6.



Figur 3 **Historisk forbruk og beregnet fremtidig levert energi til boligene i Midt-Norge for “basis –scenariet” (øverst til venstre) passivhus satsing (øverst til høyre), overgang**

til termiske energibærere (midten til venstre), passivhus satsing + overgang til termiske energibærere (midten til høyre), satsing på varmepumper (nederst til venstre), passivhus satsing + varmepumper (nederst til høyre). Venstre y-akse viser oppvarmet bruksareal i millioner m^2, mens høyre y-akse viser totalt antall GWh/år.

Tabell 6 **Oppsummering av resultater for de analyserte scenariene.**

Levert energi i år 2035 [GWh/år]						
Scenario	Totalt	Elektrisitet	Termiske energibærere	Uforandrede boliger	Rehabiliterte boliger	Nye boliger
År 2000 referanse	4.926	3.748	1.178			
Basis	5.449	3.973	1.476	2.358	1.843	1.249
Overgang til termiske energibærere	5.780	3.235	2.545	2.358	2.055	1.367
Satsing på varmepumper	4.914	4.066	848	2.358	1.498	1.058
Passivhus satsing	3.993	2.958	1.036	2.358	984	651
Passivhus satsing + termiske energibærere.	4.092	2.737	1.355	2.358	1.057	678
Passivhus satsing + varmepumper	3.833	2.986	848	2.358	867	609
Energidirektivet	4.980	3.684	1.296	2.358	1.574	1.049

Konklusjoner

Det er beregnet at om vi fortsetter å bygge- og rehabilitere boliger som før vil elektrisitetsforbruket til boligene i Midt-Norge øke fra 3748 GWh i år 2000 til 3973 GWh i år 2035. Det vil si en økning på 225 GWh/år eller 6 %.
Bruken av termiske energibærere (andre energibærere enn elektrisitet) er samtidig beregnet å øke med 298 GWh/år (25 %) fra 1178 GWh i år 2000 til 1476 GWh i år 2035.

Av tiltakene vurdert i denne studien er passivhus satsingen det som vil gi størst effekt både når det gjelder reduksjon av behov for elektrisitet og termisk energi i Midt-Norsk boligmasse. Dersom det lykkes å få til en gradvis endring fra dagens energistandard for boligene som bygges og rehabiliteres slik at alle nye boliger som bygges etter 2015 får passivhus standard (energimerke A+), mens alle boliger som rehabiliteres etter år 2020 oppgraderes til god lavenergistandard (energimerke A), er det beregnet at dette vil redusere det totale elektrisitetsforbruket i
Midt-Norske boliger fra 3748 GWh i år 2000 til 2958 GWh/år i år 2035, det vil si en reduksjon på 790 GWh/år eller 21 %. Samtidig er forbruket av termiske energibærere beregnet å reduseres med 142 GWh/år (12 %) fra 1178 GWh i år 2000 til 1036 GWh i år 2035.

Satsing på passivhus i kombinert med varmepumper er til sammenligning beregnet å redusere elektrisitetsforbruket med 763 GWh/år (20 %) fra år 2000 til år 2035, mens reduksjonen i bruk av termiske energibære da blir 330 GWh/år (30 %). Dette innebærer at varmepumpe satsingen vil bidra til en marginal økning av elektrisitetsforbruket, men vil til gjengjeld medføre en betydelig reduksjon i bruken av andre energibærere.

En omfattende omlegging fra bruk av elektrisitet til mer bruk av termiske energibærere til oppvarming er tilsvarende beregnet å bidra til en reduksjon på 513 GWh/år (14 %) med elektrisitet fra år 2000 til år 2035, men vil samtidig øke forbruket av termiske energibærere med hele 1367 GWh/år (116 %). Dette vil måtte medføre betydelige tiltak på forsyningssiden i forhold til produksjon og distribusjon av termiske energibærere.

En kombinasjon av passivhus satsing og bruk av termiske energibærere er beregnet å redusere elektrisitetsforbruket med 1011 GWh/år (27 %) fra år 2000 til år 2035, mens forbruket av termiske energibærere er beregnet å øke med 178 GWh/år (11 %). Dette er følgelig den strategien som har størst potensial i forhold til å redusere elektrisitetsforbruket i Midt-Norsk boligmasse. Samtidig gir den en økning av det termiske energibehovet er så liten at dette ikke vil medføre drastiske tiltak i forhold til termisk energiforsyning.

Forutsatt at de skjerpede energikrav i TEK 07 – Rev 07 som følge av *Energidirektivet* blir etterfulgt er det estimert at elektrisitetsforbruket til boligmassen i Midt-Norge vil reduseres med 64 GWh/år (2 %) fra år 2000 til år 2035, mens det termiske forbruket er beregnet å øke med 119 GWh/år (10 %).

En storstilt satsing på passivhus teknologi, gjerne i kombinasjon med bruk av andre energibærere enn elektrisitet til oppvarming, vil redusere behovet for etablering av ny kraftproduksjon og forsterkning av overføringskapasitet inn til Midt-Norge. Avhengig av hva som gjøres i forhold til næringsbygg, og utviklingen i industri, transport og energisektoren, kan dette bidra til å eliminere behovet for ny kraftproduksjon i Midt-Norge og forsterkning av overføringskapasitet inn til regionen i uoverskuelig fremtid. Strategier for å bedre energiytelsen til boligsektoren bør derfor inngå som en av flere viktige elementer i Midt-Norges fremtidige energi- og miljøpolitikk.

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