NTNU – Trondheim
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Dynamics of energy and carbon emissions in residential building stocks

The role of solutions for multi-family houses
and apartment blocks

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MASTER THESIS

for

Student Anja Myreng Skaran

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Dynamics of energy and carbon emissions in residential building stocks – The role of solutions for multi-family houses and apartment blocks

Endringer i boligmassens energiforbruk og karbonutslipp – Betydningen av løsninger for flerfamiliehus og leilighetsbygg

Background and objective

The background of this master thesis is the current high priority of R&D and practical implementation of new solutions for minimising energy consumption of buildings, and the corresponding expected environmental life cycle impact reductions. For this to happen it is important to understand the aggregated energy and carbon emission situation of the standing residential building stock, and its dynamic changes over time due to stock growth, stock ageing, renovation opportunities, new building codes and building occupancy behaviour. The EPISCOPE project (using the TABULA method) examines such questions for the Norwegian residential building stock, and the student studied one part of the building stock in her project work during the 2013 fall semester. Together with dynamic modelling research at IndEcol, this provides a good basis for more in-depth dynamic analysis in a master thesis.

The objective of this master thesis is to contribute to the understanding of long-term dynamics of energy and carbon emissions in residential building stocks. The student shall focus on the role of solutions for multi-family houses and apartment blocks, including scenarios for refurbishment strategies, energy generation and occupancy behaviour. Additionally, the student shall examine the influence of life cycle energy costs.

The following tasks are to be considered:

1. Carry out a literature study on state-of-the-art strategies, technologies and/or methods that are relevant for your work.
2. Provide a systems definition of the system you are analysing, including description of goal and scope, system boundaries, data inputs and assumptions, for selected scenarios and/or configurations of technological solutions within your system.
3. Develop a quantitative model for your system, including relevant indicators and/or metrics that can be used to document the energy and carbon emission performance of the system.
4. Report results from the energy and carbon emission performance analysis of your system (including scenarios and/or configurations of technological solutions) and the particular importance of critical system variables, components or assumptions leading to these results.
5. Discuss the overall findings of your work, agreement with literature, strengths and weaknesses of your methods, and possible practical and/or methodological implications and recommendations of your work.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his/her project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analysed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14th January 2014

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Summary

A decrease in energy consumption is an important part of the effort to reduce fossil emissions. Buildings contribute to a considerable share of the energy consumption in Norway, mainly because of the cold climate and low energy prices. Building regulations today set low limits for maximum energy use for heating, but existing buildings have a higher potential for reductions, as the maximum energy limit has changed over the years. This report covers possible strategies for reducing energy demand in a specific part of the Norwegian building stock: Apartment blocks constructed between 1981 and 2010.

Earlier projects have also evaluated the energy reduction potentials in the Norwegian dwelling stock. However, this has mostly been done on an aggregated level, and as buildings vary greatly in size, location, and age, the same recommendations cannot be expected to apply to all buildings. The effects of rehabilitations and demolitions on the building stock are often simplified to linear behaviour, but this is not accurate.

Calculations were carried out on defined standardised buildings in a climatic zone represented by Oslo. First, an energy balance was established for evaluating the energy consumption of the various buildings, both in their original state, and subject to various combinations of rehabilitations to heating system, insulation, and ventilation. Then, heating-related costs were calculated in order to find the options with the lowest net present value, based on an investment horizon of 36 years. Based on these results, possible scenarios for energy use and CO_2 emissions were calculated for the years 2014-2050, based on the average building being rehabilitated after 40 years.

In line with other studies, the energy consumption in the original buildings were found to be low, and close to the current TEK 10 regulation, which must be followed if major rehabilitations are conducted. Hardly any rehabilitations were found to be profitable with the costs of today, and a doubling of the electricity costs affected the outcome to a small degree only. In most cases, the best option is to change as little as possible, although replacements of windows and doors were profitable for the oldest buildings. Using electric radiators for all room heating is the most common heating system today, but this is not in line with the TEK 10 standard. If the heating system is to be changed, air-air heat pumps are the best alternative. However, the savings from these depend highly on climate conditions. Fuel oil heaters are the least profitable option, and these should be removed, as is mandatory soon anyway.

Demolitions alone result in a 15 % energy reduction within 2050, close to the scenario based on lowest possible costs at 21 %. The low emissions case results in a 50 % reduction, while rehabilitations to zero energy buildings would reduce the energy by 72 %. No official reduction target is presently set for Norway, although a 50 % energy reduction between 2010 and 2040 has been expressed in a report for the former Government. This target is only possible to reach with zero energy upgrades. Emissions follow similar paths as the energy when Norwegian electricity mix is used as a basis. However, definitions on electricity mix and related emissions affect the results more than the chosen energy rehabilitations when estimating total emissions.

Sammendrag

Reduksjon av energibruken er en viktig del av arbeidet med å minske utslippene fra fossile energikilder. Bygninger står for en stor andel av energibruken i Norge, først og fremst på grunn av kaldt klima og lave energipriser. Dagens bygningsforskrifter setter strenge krav til maksimal energibruk til oppvarming, mens eksisterende bygg har et større potensiale for energisparing, siden kravene har blitt satt gradvis strengere over tid. Denne rapporten omhandler mulige strategier for energireduksjon i en bestemt del av den norske bygningsmassen: Leilighetsblokker bygget mellom 1981 og 2010.

Tidligere prosjekter har også evaluert energireduksjonspotensialene i den norske boligmassen. Dette har imidlertid blitt gjort på et overordnet nivå, og siden størrelse, beliggenhet og alder i stor grad varierer, kan ikke de samme anbefalingene forventes å gjelde for alle bygg. Effektene av rehabilitering og rivning av boligsmassen er ofte forenklet til å ha lineær oppførsel, men dette er ikke en nøyaktig fremstilling.

Utregninger har blitt gjennomført for definerte standardbygg i Oslo-klima. Først ble energibalansene for bygningene etablert, både i originaltilstand og etter gjennomførte energitiltak på isolasjon eller energi- eller ventilasjonssystemet. Etterpå ble varmerelaterte kostnader regnet ut for å finne kombinasjonene med lavest netto nåverdi, basert på en 36 års investeringshorisont. Ut i fra disse resultatene kunne aktuelle scenarioer for energibruk og CO_2-utslipp regnes ut for perioden 2014-2050, basert på at gjennomsnittsbygg skulle bli rehabilitert etter 40 år.

I likhet med de andre studiene ble energibruken for originalbyggene funnet til å være lav, og i nærheten av den nåværende standarden, TEK 10, som må følges ved store rehabiliteringer. Nesten ingen av de andre rehabiliteringene endte opp som lønnsomme med dagens kostnader, og en dobling av elektrisitetsprisen påvirket resultatet kun i liten grad. I de fleste tilfellene viste den beste løsningen seg å være å endre så lite som mulig, selv om utskifting av vinduer og dører kunne være lønnsomt for de eldste byggene. Elektriske panelovner til all romoppvarming er det vanligste systemet i dag, men dette tilfredsstiller ikke kravene i TEK 10. Hvis oppvarmingssystemet skal endres, er luft-til-luft-varmepumper det beste alternativet. Besparelsene for dette systemet varierer imidlertid etter uteklimaet. Oljekjeler er det dyreste alternativet, og disse bør fjernes, noe som blir påbudt snart uansett.

Rivninger i selg selv fører til en energireduksjon på 15 % innen 2050, noe som er svært nært rehabiliteringspakken som baserer seg på lavest mulige kostnader, på 21 %. Rehabiliteringspakken med lavest utslipp halverer energiforbruket, mens rehabiliteringer til nullenerginivå resulterer i en endring på 72 %. Det finnes ingen offisielle reduksjonsmål i Norge, men en halvering av energibruken fra 2010 til 2050 har blitt nevnt i en tidligere rapport for Kommunal- og regionaldepartementet. Dette målet kan bare nås ved hjelp av nullenergirehabiliteringer. Utslippene følger lignende mønster som energibruken når norsk energimiks brukes som grunnlag. Det viste seg imidlertid at definisjonen av energimiks og tilhørende utslipp påvirker resultatene mer enn de valgte rehabiliteringspakkene når totale utslipp skal beregnes.

Contents

List of abbreviations

BRA	=	available area (Norwegian: bruksareal)
DHW	=	direct hot water
DT	=	design temperature
EPBD	=	energy performance building directive
GHG	=	greenhouse gases
LCA	=	life cycle assessment
LCC	=	life cycle costing
NPV	=	net present value
NS	=	Norwegian Standard
NZEB	=	nearly zero energy building
PV	=	photovoltaic
TEK	=	Byggteknisk forskrift (technical building regulation)
SSB	=	Statistics Norway
ZEB	=	zero energy building

List of symbols

DT_e	=	external design temperature [°C]
DT_i	=	internal design temperature [°C]
λ	=	heat conductivity [W/mK]
P_{dim}	=	design heat load [kW]
U	=	coefficient of thermal transmittance (U-value) [W/m^2K]

All symbols used in the TABULA equations are gathered in App. A.1.

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1 Introduction

Reduction of global energy consumption is important in order to limit emissions and depletion of fossil energy sources. Buildings account for 40 % of the total Norwegian energy consumption. Because of the long lifetime of a building, older buildings still make up a large share of the present building stock. These have a higher energy demand than those constructed today, and can also utilize more carriers with high emissions, such as fuel oil. In order to improve these buildings, energy rehabilitations such as retrofit insulation or installation of heat pumps, are necessary. Both Norway and the EU have set regulations regarding energy consumption in the building stock, but more research remains on the strategies best suited for reaching the targets.

This report is a part of a research project where the future energy consumption in the Norwegian building stock is evaluated. The building stock share chosen for calculations in this report is Norwegian apartment blocks constructed between 1981 and 2010, and related rehabilitation strategies for reducing energy for direct hot water and room heating. The buildings are split in three age groups, and properties of the buildings in their original state are established. This is done after conducting a literature study, where current regulations and previous studies on earlier energy development and rehabilitations are examined. Information from this is used further for establishing some standardised renovation packages for the chosen building cohort. The benefits of these will be evaluated by calculating the energy reduction and economic saving potential following the various rehabilitations.

The energy balance calculations are based on the TABULA method - a standardised model developed by the EU's Intelligent Energy Europe for calculating energy consumption for heating in buildings. An evaluation on the suitability of this model for this project is a part of this project. Costs will be calculated based on a life cycle costing assessment of all installation and maintenance related to building insulation, air leaks, and energy source, as well as energy costs. The net present value of all costs between the years 2014 and 2050 is to be used as a basis for choosing the most beneficial rehabilitation packages.

Based on the results from these two calculations, scenarios for future energy consumption for heating of apartments, as well as related CO_2 emissions are evaluated. Factors such as population growth, renovation and demolition rates, occupant preferences, emissions from energy carriers, and future building regulations are all factors that will contribute to this development, and previous studies on these factors will also be included. In order to predict the future developments, a building stock scenario model is used for the calculations. This model is provided by the Industrial Ecology Programme at NTNU, where it is currently used in dynamic modelling research.

The report aims to answer these main questions:

- Which types of renovations are the most beneficial when rehabilitating newer apartment blocks, and how can these choices affect the future energy consumption and emissions?
- How can factors such as energy costs and rehabilitation rate affect the outcome?
- How do the various scenarios match the current policy targets, and what can be done in order to increase energy reduction by rehabilitation?

Answers to these questions will be helpful for both building owners when making efficient rehabilitation choices, and for policy makers when selecting efficient incentives and targets for emissions reduction.

Calculations of energy balance, costs, and future energy consumption and emissions will be done in separate spreadsheets in Microsoft Excel. Underlying definitions and equations are presented in the Method section, and main results will be presented in the Results sections or Appendix in this report. The models themselves, as well as all results are gathered on a CD provided with the report.

2 Literature study

2.1 Project basis

2.1.1 Background

The information in the following two paragraphs has been gathered from a pamphlet by Norsk teknologi (2013), unless marked otherwise. The total global energy use has increased by 1.8 % every year from 1980 to 2009, and is estimated to continue to increase by 40 % in total towards 2035. Consumption of fossil energy is also expected to increase, although its share of the total energy consumption will decrease. With this predicted energy consumption and energy mix, large investments will have to be made by the global community, and problems with climate change and the distribution of natural resources will arise. According to the UN, the global emissions of climate gases must be reduced by 50-80 % towards 2050 in order to maintain a sustainable climate. In order to reach this target, both energy efficiency and a transition to renewable energy is required.

Construction and operation of buildings contribute to about 15.5 % of the climate gas emissions globally, and about 36 % in Europe. The EU has introduced ambitious energy efficiency measures, such as the target of reducing climate gases by 20 % from 2005 to 2020. On the other hand, Norway has currently no national target planned action for increasing the energy efficiency. This might seem like a reasonable priority, as the share of Norwegian climate gas emissions connected to buildings are only 3 % of the total emissions. However, as building-related energy accounts to almost 40 % of the total Norwegian energy consumption, there are other great advantages connected with energy efficiency, such as the opportunity to transfer low-emission energy to other sectors or to export it. Many energy efficiency measures for buildings are also connected with economical savings. Fig. 1 illustrates the costs connected to various energy efficiency abatements on the global level. Noticeably, all building related abatements considered in the analysis have been found to be profitable.

Despite the profits connected to energy-related renovation, the potential is far from being fulfilled in Norway. Reasons for this might be lack of knowledge on the building owners' side, or the fact that building renovation often comes with high investment costs, while the potential savings are less certain, and set to the future. If the costs are evaluated over a longer period of time, and as many cost aspects as possible are covered, a more realistic cost analysis will follow, and the more likely it is to show that the measure is profitable. A life cycle costing (LCC) analysis[i]is a good tool for such an economic analysis. In this way, the most profitable options can be identified. This is also useful for predicting the future development of the energy use in the building stock, in order to compare goals to current situations, and develop political measures. Increasingly strict policies for energy use in new buildings might ensure that future buildings will be energy efficient, but as a residential buildings might last for a decade or more after construction, the current building stock will continue to dominate the future building-related energy consumption.

2.1.2 Previous work

Arnstad (2010) developed a report for The Norwegian Ministry of Local Government an Regional Development in order to prepare proposals for goals and develop a schedule for increasing

[i]Described in Chap. 3.4.

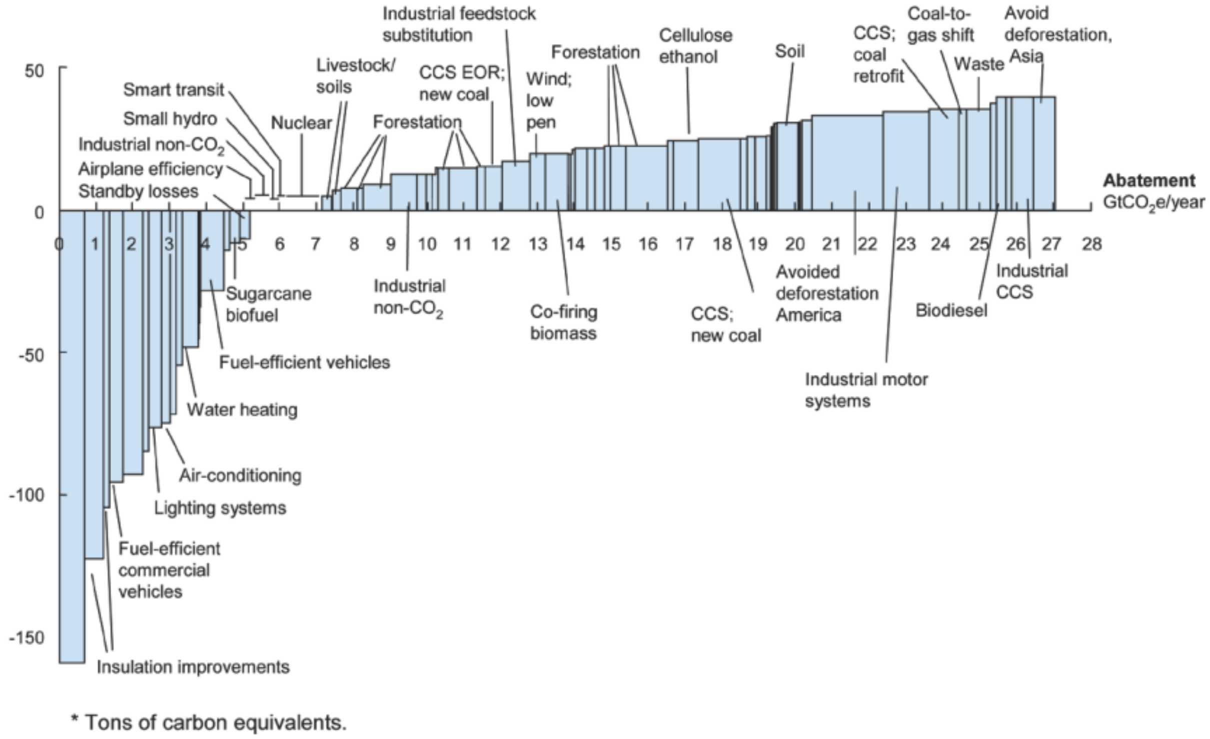

Figure 1: Cost of abatement for various abatement opportunities, 2030, €/tCO_2e (Beinhocker et al., 2008)

the energy efficiency of the building stock. It suggests a goal of 10 TWh reduction in yearly delivered energy for building operations within 2020, compared to today's level of 80 TWh, and a reduction of 40 TWh within 2040. Judging from today's rate of construction and demolition, at least 8 TWh of the reduction of 10 TWh must be collected from the existing building stock, as it takes years until the buildings constructed now and in the future years will constitute a significant volume of the total Norwegian building stock (Førland-Larsen, 2012). Arnstad (2010) explored the challenges and possible political solutions for energy efficiency measures in the building stock, but did not evaluate costs and technical solutions in detail.

Hille et al. (2011) developed a scenario model for Norwegian energy use towards 2030. Building area, building types, building envelope, heating sources, outdoor and indoor temperature, demographical changes, technological development, economy, user behaviour, and political instruments were all taken into consideration in the report. However, the project was more focused on identifying the drivers for energy use, rather than examine the specific effects of rehabilitation measures on the energy use. Also, the building categories were not sorted by construction year. One of the main conclusions of the report was that the largest energy saving potential was in existing buildings, rather than those remaining to be built.

A similar analysis was carried out in a report by Mjønes et al. (2012), but with a larger emphasis on technical solutions, a shorter time horizon (towards 2020), and with more and narrower building definitions. This report sorted the building stock into groups depending on building type, location, and time of construction (usually within time intervals of ten years). The energy efficiency measures were calculated by defining certain energy rehabilitation packages for existing buildings. These packages were based on profitable solutions when raising the buildings to TEK 10 standard[ii] for older buildings and class 1 low energy building standard[iii]for newer buildings. Existing apartment dwellings constructed after 1980 were concluded to have almost no energy saving potential in this report, as the report identified few upgrades on this

[ii] Norwegian building regulation from 2010. More on this in Chap. 2.3.2.

building typology as profitable. However, the economic analysis done in this report seems to be on the shallow side. The report does not describe their basis for calculating costs, nor the time horizon for calculating savings over time. Also, buildings must be rehabilitated periodically as part of ordinary maintenance, and when combining energy efficiency measures with these rehabilitations, the additional investments for energy rehabilitation are likely to be significantly smaller. The report does not seem to take this into account, but compares the costs to a scenario where no rehabilitations are done to the buildings.

Førland-Larsen (2012) analysed the costs of energy rehabilitation more thoroughly, in order to find the building components best fit for rehabilitation. The report concluded that the costs and building types vary to such an extent that it is not possible to choose some components for which renovation will always be profitable, but that energy rehabilitations generally are profitable for buildings constructed before the TEK 10 requirements were enforced. Retrofit insulation was not found to be profitable for buildings of TEK 10 standard, but exchanging windows and doors for passive house standard components could possibly lead to lower costs. Some cost calculations were done for newer and older apartment blocks separately, but the report did not draw any conclusions for these buildings on a detailed level.

The reports above that predict the future developments of the building stock are based on the simplification where the construction development is assumed to be linear and a set renovation and demolition rate of a certain percentage are assumed. Sandberg et al. (2014) are continuing the work on a dynamic model for simulating the rate of construction, renovation, and demolition of the dwellings in the Norwegian building stock, separated by compact and detached houses, for the time period 1800 to 2100. As empirical data on demolition and renovation are not available, the rate of these are simulated using a Weibull or Normal distribution. The report concludes that energy renovations will increase strongly in the future, but with the current rehabilitation period of 40 years, this is not enough for reaching policy targets. Older, detached houses will remain the most important area for renovation activities in the future.

Pauliuk et al. (2013) studied energy reduction potentials for the Norwegian building stock, using a dynamic stock model, and a combination of MFA (material flow analysis) and LCA (life cycle assessment) techniques in order to investigate outside the boundary of the direct emissions. The building stock was divided by dwelling type, and the energy demand after various rehabilitation combinations were presented for all of the buildings. With the most ambitious rehabilitation measures, the reduction potential for both energy use and CO_2 emissions were found to be 75 %.

In order to track the effects of energy refurbishment on national building stocks in European countries, various institutions in Europe (including NTNU) are cooperating on a project called EPISCOPE. This project focuses on building typologies, building stock monitoring, and scenario analysis. The goals are to establish a set method for monitoring energy use, comparing the results to the policy targets and to other countries, and recommendations for energy measurements and how to monitor them. The building types that are to be examined in this project are existing buildings, new buildings and Nearly Zero Energy Buildings (NZEBs) (Institut Wohnen und Umwelt GmbH, 2013a). The conceptual framework of the EPISCOPE project will be based on the building typologies from the finished IEEE project TABULA (Institut Wohnen und Umwelt GmbH, 2013a). Similarly to EPISCOPE, this project was done in collaboration between European institutes, but Norway was not involved. In TABULA, residential building typologies were developed for 13 European countries. These typologies were classified according to age, size, and other parameters. Additionally, energy related features and possible energy savings from refurbishments were calculated for example buildings from each category (Loga

[iii]Defined in NS 3700 (Standard Norge, 2013). More on this in Chap. 2.3.2.

et al., 2012c). This methodology will be use as a basis when calculating the energy demands of the various buildings in this master thesis.

2.1.3 Building definition

The building type chosen for examination in this project is Norwegian apartment blocks, constructed in 1981 or later. The TABULA method does not specify any common definition of apartment blocks; instead, the building definitions vary among the project countries (Loga et al., 2012b).

Mjønes et al. (2012) define apartment blocks as detached blocks of housing units, consisting of concrete elements. They further state that the units are small, contain one inhabited floor each, and that the building type consists of 18 units in average, spread over 4 floors. The report is based on statistical data from this report and Statistics Norway (SSB).

SSB uses two different definitions of apartment blocks, according to SINTEF Byggforsk and NTNU Samfunnsforskning (2009): For SSBs centennial populations and housing census, all dwellings of 3 floors or more are counted. In their general building statistics, the definition is any dwelling of more than 2 floors and with at least 5 apartments.

Most other major sources in this project do not include a clear definition of which buildings they include in the term "apartment blocks". It is, however, likely that Norwegian numbers are based on research from SSB, and SSBs two definitions are not different enough to indicate that they will produce significantly different results. Therefore, the numbers from the various sources are from here on assumed to involve the same buildings.

2.2 Past developments

2.2.1 The building stock

Fig. 2 and Fig. 3 describe the development of the Norwegian residential building stock in terms of area and building type. Apartment blocks were less popular between 1981 and 1990, but have later become increasingly common again. According to Fig. 3, the total area of new buildings has also decreased since this time, stabilising after 1990. This is assumed mainly to be caused by a considerable increase in real estate prices and interest rates, and the increase of immigrants, who have access to smaller living areas than other Norwegians in general (Hille et al., 2011).

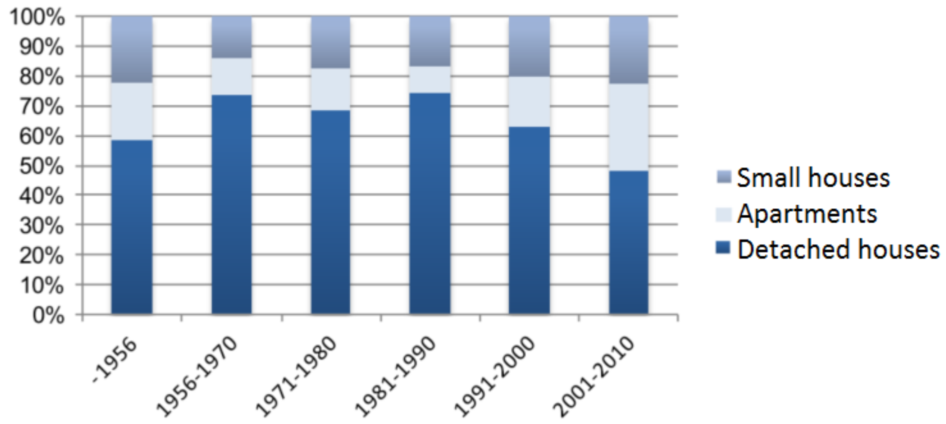

Figure 2: Distribution of dwelling types in Norway by share of total area per time frame, sorted by year of construction, pre-1956 to 2010 (Mjønes et al., 2012).

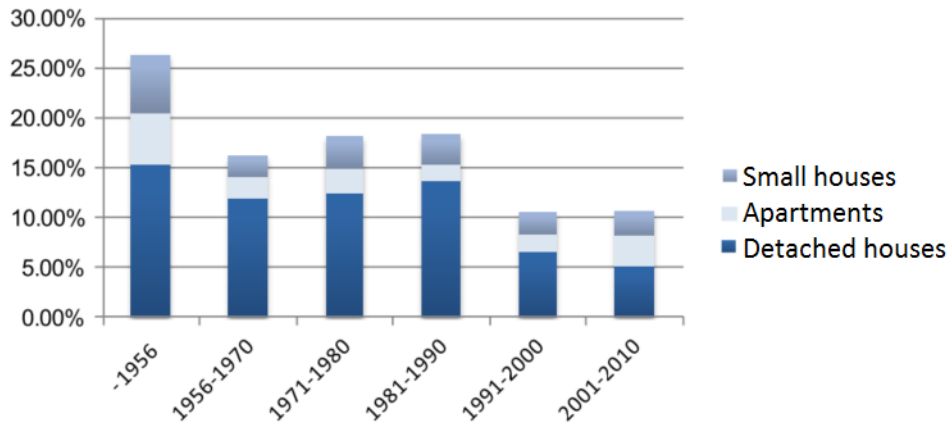

Figure 3: Distribution of dwelling types in Norway by share of total area, sorted by year of construction, pre-1956 to 2010 (Mjønes et al., 2012).

Although the newly constructed building area has sunk, this trend does not apply to apartments. Table 1 shows that both the number and area of apartments have increased for the relevant time frame. The average area has shrunk between the two first time frames, again to increase slightly in the most current past, resulting in a standard building size identical to that of the total average over time. Compared to the total amount of dwellings in Norway, apartments constructed in the time scale of this project (1981 - 2010) represent 41 % of the total apartment area and only 6.6 % of the total building stock constructed before 2011. The average block consists of 24 apartments (Mjønes et al., 2012).

Table 1: Amount and area of Norwegian existing apartment buildings, sorted by construction year (Mjønes et al., 2012)

Construction year	Number of apartments	Average area per unit $[m^2]$	Total area $[m^2]$
1981-1990	56,379	76	4,310,185
1991-2000	63,820	69	4,835,626
2001-2010	115,080	71	8,114,649
Total, 2010 and earlier	593,598	71	42,126,802

2.2.2 Energy consumption

The energy consumption for Norwegian buildings differ from that for buildings in other parts of Europe, mainly because of the cold climate. Norwegian residential buildings need most of the energy for heating purposes, and traditionally no or very little energy for cooling purposes. Additionally, Norway has an abundance of cheap electricity and firewood, which makes these the main energy sources, as opposed to other European countries, where sources such as oil, gas and district heating are more common (Laustsen et al., 2011). Therefore, Norway has the lowest CO_2 emissions per useful floor area of all the European countries (Laustsen et al., 2011).

According to Hille et al. (2011), the direct main drivers (physical properties) for energy use are:

- Building area
- Distribution of building types
- The building envelopes
- Indoor temperature
- Energy demand for DHW (direct hot water)
- Energy demand for lighting and electrical appliances
- Choice of heating system
- Heat pumps

And the indirect drivers (uncontrollable or society-related factors) are:

- Outdoor temperature
- Demographical changes
- Economy
- Technological advancements
- Change in knowledge, attitude, or preferences of the occupants
- Political measures

Fig. 4 shows an overview of the development of the total Norwegian residential energy demand. The energy demand has increased from around 32 TWh/year to around 48 TWh/year in 2010. Electricity has been the main heating source for the entire period of time, while fuel oil has decreased substantially. Firewood was the second most common heating source in 2010, and the use of firewood has been more or less stable since the 1980 centennial. District heating and gas represent a tiny share of the energy sources.

The energy use is naturally greatly affected by the outside temperature. In order to identify the impacts of other, and more controllable factors, the energy use can be adjusted for the outside temperature, such as done in Fig. 5. In general, this gives a higher energy use in the beginning of the period, and lower energy use after around 1997, compared to the actual energy use. This means that the winters have become warmer in general, and that the energy demand unrelated to room heating has increased more than the residential energy demand in general. 2010 was an especially cold year, which explains the peak in the energy use. Looking at the energy use adjusted for temperature, it is apparent that the energy demand seems to

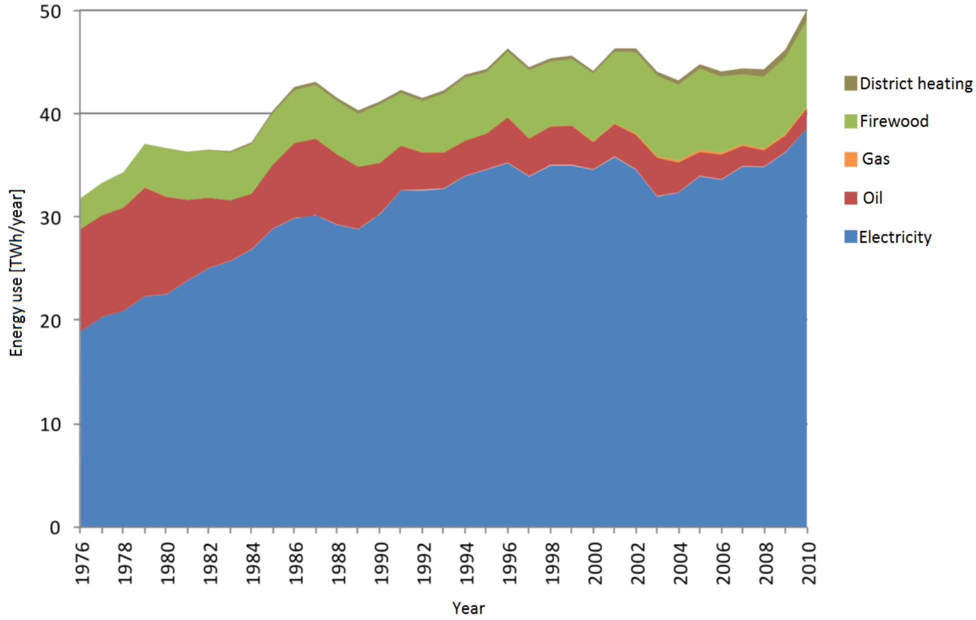

Figure 4: Total Norwegian domestic energy use 1976-2010 in TWh supplied energy, sorted by energy carrier (Bergersen et al., 2012)

have stabilised at the end of the century. The growth in energy demand before 1996 was mostly due to population growth and larger living spaces per person (Bøeng, 2005). Hille et al. (2011) researched the reasons for the recent stabilisation, and found that the main factors were a decrease of the average building area, reduced energy use per area, and to a smaller degree, the warmer weather.

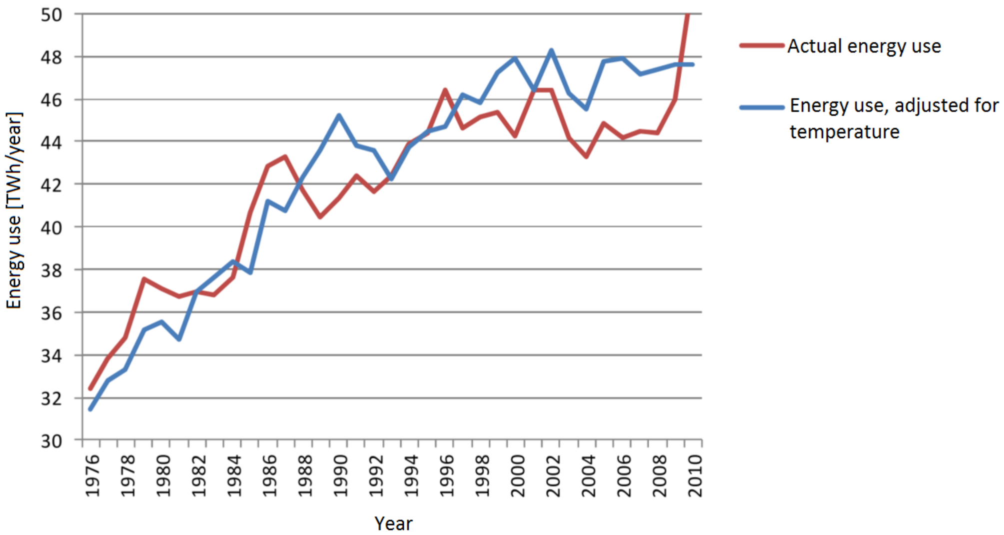

Figure 5: Development of the total Norwegian domestic energy use in TWh/year, and adjusted for variations in outside temperature 1976-2010(Bergersen et al., 2012)

It can be seen from Fig. 6 that the average energy use for Norwegian households was almost at the same level in 1960 and 2004 - slightly increasing at first, then turning to decrease around 1987. (The significant dip in 1974 was caused by the oil crisis in 1973-1974 when fuel oil prices were doubled, combined with a warm year (Bøeng, 2005, p. 12).) The most important factors for the decrease in energy use per area are energy saving measures in old buildings, introduction of heat pumps, more efficient heating, new technical building standards, and reduced energy use for DHW. The development of the indoor temperature is unknown, and this is therefore a possible, but uncertain factor (Hille et al., 2011).

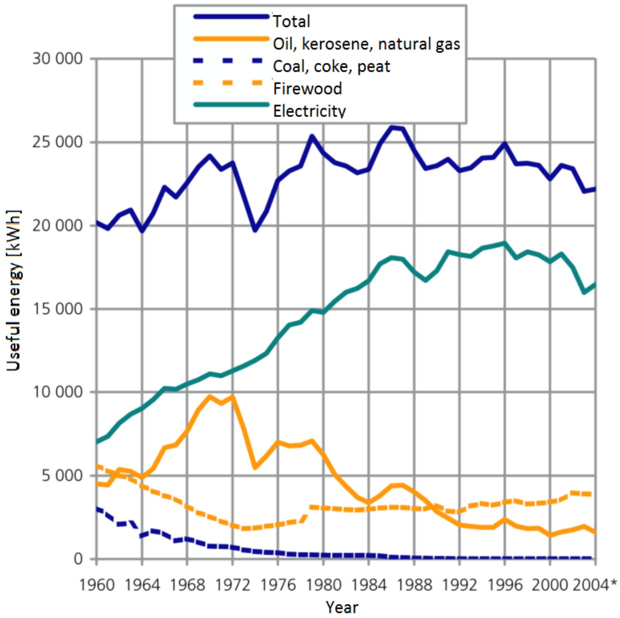

Figure 6: Norwegian average energy use per household 1960-2004 in kWh supplied energy, sorted by energy carrier. *Based on temporary values at the time (Bøeng, 2005)

Fig. 7 shows how the energy use varies depending on building type and construction year. The energy consumption has decreased slightly for apartment blocks between the last two time frames, continuing the historical trend, while the other building types stay on the same level for the last two time frames. However, the energy specific demand [kWh/m^2] in apartment blocks has increased slightly since around 1980, which is the opposite of the trend for the other building types (Hille et al. 2011). This indicates that there is a need for energy saving measures in this part of this building stock.

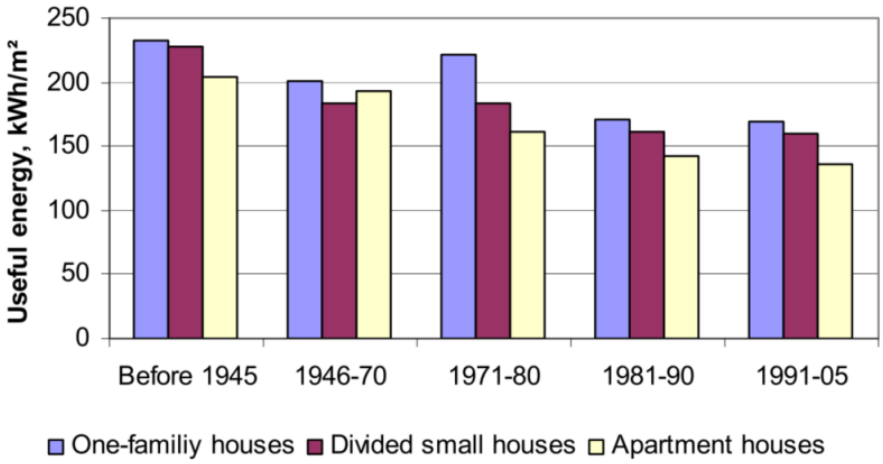

Figure 7: Average specific net energy consumption for the stereotypical Norwegian residential buildings (Thyholt, 2009).

According to Hille et al. (2011), out of the delivered energy for a typical apartment, 30 % is used for DHW (including losses from the storage tank of 5 %), 23 % for room heating, 5 % for lighting, 28 % for appliances, and 16 % for technical operations. The room heating share is about a third of that of the other buildings types. This implies that heat saving measures are less important for this building type than for the other ones.

No statistics have been found for energy purposes sorted by building construction year. However, Mjønes et al. (2012) has defined such values for stereotypical dwellings, and these are collected in Table 2. As the standard dwellings are based on statistical data from SSB, among others, these values can be considered a useful guideline. However, the Total values in Table 2 are quite lower than the values seen in Figure 7, which are considered as the most realistic. Ergo, the standard apartment blocks should not be regarded as average blocks.

Table 2: Delivered yearly energy for standard apartment blocks, sorted by year of construction and energy purpose(Mjønes et al., 2012)

	Energy consumption [kWh/m^2] (% of total)			
Construction year	Total	Room heating	Fans	DHW
1981-1990	108.0	48.4 (44.8 %)	0.7 (0.6 %)	30.0 (27.7 %)
1991-2000	110.0	50.0 (45.5 %)	0.7 (0.6 %)	30.0 (27.3 %)
2001-2010	120.0	53.8 (44.8 %)	7.3 (6.6 %)	30.0 (25.0 %)

In 2010, the total Norwegian building stock had a net energy consumption of 28.52 MWh. Apartment blocks contributed to 6.59 TWh of these, and the apartments built later than 1980 had an energy use of 2.46 TWh (Mjønes et al., 2012), which is 8.6 % of the total energy consumption of the building stock.

Taking the life cycle aspect into consideration, an energy analysis of the building stock should also include energy demand for construction, maintenance, and demolition, and a thorough life cycle assessment (LCA) would also include factors such as recycling and production of materials, etcetera. A review article conducted by Sartori and Hestnes (2007) show that these embodied energy demands generally are small compared to the energy demand during operation of the building. However, for low energy buildings, the embodied and operational energy demand are close to the same level. Thus, the energy sources for building operations will be less crucial for the life time energy demand of buildings in the future. In order to limit the scope of this project, only direct energy demand during operation will be evaluated.

2.2.3 Building envelope

Typical compositions of apartment walls, ceiling, and floor are gathered in Table 3 to Table 5, sorted by construction year.

Table 3: Typical composition of apartment walls 1981-2010 (Mjønes et al., 2012)

Construction year	Composition	U-value [W/m^2K]
1981-2000	Wood frame house, 150 mm mineral wool, 50 mm thermal breaker	0.29
2001-2010	Wood frame house, 200 mm mineral wool, 50 mm thermal breaker	0.27

Table 4: Typical composition of apartment ceiling 1981-2010 (Mjønes et al., 2012)

Construction year	Composition	U-value [W/m^2K]
1981-2000	Concrete slab, 180 mm mineral wool	0.2
2001-2010	Wood frame house, Hollow core slabs, 220 mm mineral wool	0.14

Table 5: Typical composition of apartment floor 1981-2010 (Mjønes et al., 2012)

Construction year	Composition	U-value $[W/m^2K]$
1981-2000	Concrete floor, 120 mm mineral wool	0.2
2001-2010	Hollow core slabs, 220 mm mineral wool	0.14

Mjønes et al. (2012) provide U-values for properties of typical apartments from different construction years. The U-values for windows and doors from the typical apartment block built between 1981 and 1990 are 2.2 and 2 $W/m^2 \cdot K$, respectively. Windows and doors in the typical 1991-2000 apartment block have a U-value of 2 $W/m^2 \cdot K$, and the U-value is 1.6 for the newest age cohort. Broli (2000) provides a table for matching U-values with window types. By looking at these two sources in combination, the development of the typical window type can be estimated. For the early buildings, two-layered, sealed insulated windows with one metal coated glass, filled with air was the most common. Newer window technology has been developed in order to decrease the U-values. These include additional metal coated glasses and argon filling (Broli, 2000).

Thermal bridges appear where materials with different conductivity meet, and cause additional temperature leakages. Calculating thermal bridges is complicated, and it is often done with computer programs. Table A4 in NS 3031 defines typical thermal bridges for newer buildings, based on the insulation thickness and thermal bridge barriers in the wall. The wall type with 20 cm thick mineral wool insulation and 5 cm thick thermal bridge barrier matches the typical walls in the newest buildings, which gives a thermal bridge value of 0.12 W/m^2K. The oldest buildings have less insulation, and the thermal bridges should therefore be higher. However, as thermal bridges vary to a large extent, good example values have been difficult to find. Therefore, the standard TABULA value for a building with high effect of thermal bridges (Loga and Diefenbach, 2012a) will be used as a basis: 0.15 W/m^2K.

2.2.4 Air heating and ventilation

The preferred heating source for indoor air has not been constant over the years, as demonstrated in Fig. 6. This chapter aims at finding the most common heating source combinations for buildings constructed in the three periods of time defined for calculations in this project.

In the literature, the share of energy sources of the total energy use is often provided, but not the way the various energy sources usually are combined in a house. A building can have one or more heating sources. When using two heating sources, one is usually dimensioned to cover the base load (most of the energy demand) and the other one covers the top load (the additional energy needed in the coldest days). An energy source for base loads should be cheap in use (but might be expensive to install), while a base load energy source can be more expensive in use, but should be cheap to acquire and install. Stene (2001) describes typical dimensioning when using a heat pump as a base load: The top load is usually dimensioned to cover 100 % of the power demand at the design temperature (DT), in case of failure of the base load. The base load typically covers 60-80 % of the power demand at DT, thus covering 85-95 % of the total energy demand.

Existing buildings in general

15 % of the existing apartment blocks have a centralised heating system, excluding district heating (Hille et al., 2011). About 60 % of the energy is covered by air-air pumps where these are installed.

The energy distribution for the stereotype apartment buildings defined by Thyholt et al. (2009) is 65 % direct electricity, 13 % firewood, 10 % heat pump (air to air), 7 % oil and gas, 5 % electrical floor heating, and 0 % district heating. This means 70 % electric heating, excluding heat pumps. These values do not change over time, which suggests that this is a less accurate description.

1981-1990

According to a survey on existing buildings conducted by Ljones (1984), 85 % of the apartment blocks built after 1970 utilised electrical heating as their main heat source, either from radiators or floor heating. This was a doubling from the previous time frame. 2 % of the apartments burned solid fuels in stoves as their main heating source, while 13 % had a centralised heating system. 93 % of the central heating systems (all buildings considered) were heated using oil. Electricity had increased since the 1960 decennial, on account of central heating, solid fuel, and liquid fuel burned in stoves. Of all buildings in 1983, 50 % of the buildings with central heating as the main heating source had an additional heating source, and the most common was electricity. For the buildings with electricity as main heating source, the share was 69 %, and the most common additional heating source was wood-burning stoves. Looking at the total building stock, having only one heating source was more common for apartment blocks than buildings in general (70 %), and it was also increasingly common over time.

1991-2000

Calculated from the values provided by Bøeng (2005), the fuel distribution for dwellings in 2001, constructed in 1991 or later is: 85.5 % electricity, 0.6 % fuel oil or kerosene, and 13.9 % wood, coal, or coke.

The energy sources for apartment blocks in 2011 can be read from Table 6. The majority of apartment blocks constructed after 1990 have probably kept their original heating sources, and so the typical original buildings should have a somewhat similar energy mix as the values given in the table. Mjønes et al. (2012) comment that the installation of heat pumps has increased significantly over the last years, and the original energy share for heat pumps must therefore be lower for original buildings than what is suggested in the table.

Table 6: Total share of energy carriers in existing Norwegian apartment blocks, sorted by year of construction (Mjønes et al., 2012)

Construction year	Electricity	Wood and pellets	Heat pump	Other[iv]
1981-1990	81 %	1 %	7 %	11 %
1991-2000	93 %	2 %	6 %	0 %
2001-2010	83 %	7 %	3 %	7 %

[iv] Oil and kerosene, transition to district heating and gas.

2001-2010

It is clear from Table 6 that the electricity share decreased again after 2000, and it seems like wood and other energy sources should be taken into account again. The table does not clarify whether the energy is released in stoves or in centralised water-heated systems. However, Amundsen (2011) points out that wood-burning stoves in apartments are less common than earlier, and from a table by Skjerve (2013, p. 10), hydronic heating was installed in 85 %[v]of the buildings constructed by Norsk Boligbyggelag in 2012. Assuming that the popularity of hydronic heating has increased for some years, this implies that a typical building with hydronic heating from the 2000 centennial burns wood or pellets in a central boiler. The "Other" category mainly represents district heating for buildings from this construction time.

New buildings

Of the buildings constructed by Norsk Boligbyggelag in 2012 (Skjerve, 2013), 21 % of the buildings had equipment for electric heating (excluding heat pumps) installed, 9 % had chimneys, 78 % had hydronic heating by district heating, 7 % had hydronic heating by geothermal heat pumps, 1 % had air-air heat pumps, and 6 % had other heating source equipment. Where direct electricity or direct heating was installed, these systems were used as main heating source.

Fig. 8 shows the past development for heating sources in Norwegian dwellings. The statistics cannot be applied directly to apartment blocks, but it is interesting to note the changes for the buildings newer than 2000. Kerosene has disappeared as an energy source, and fireplaces are on a decrease, while hydronic heating and stoves heated by bioenergy or gas are gaining popularity. This can also give an indication of the rehabilitation preferences in the near future.

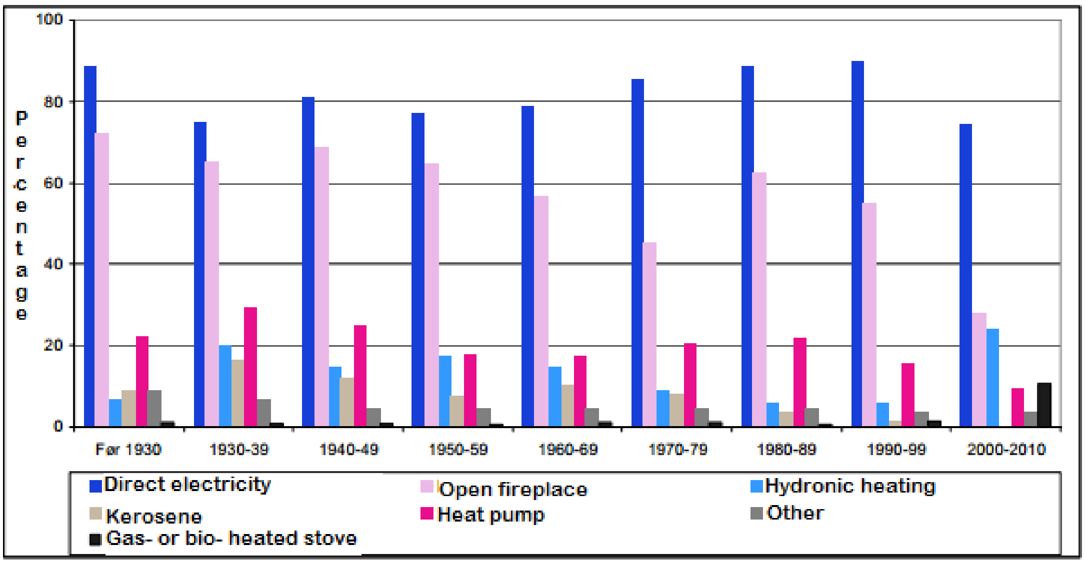

Figure 8: Installed energy systems for heating in dwellings, sorted by construction year (Amundsen, 2011)

Typical efficiencies between 1981 and 2005 are 100 % for electricity, 55 % (for construction years 1981-1990) to 60 % (construction years 1991-2005) for firewood, 250 % for heat pump (air to air), 80 % for oil and gas, and 88 % for district heating (Thyholt et al., 2009).

[v]Assuming that the categories hydronic heating by district heating and hydronic heating by ground-heated heat pump do not overlap.

Ventilation

In order to achieve satisfactory indoor air quality, fresh outside air must be delivered to the building. This happens via infiltration and ventilation. The development of these building qualities are described by Mjønes et al. (2012), and all information on ventilation in this chapter will be based on their report, unless marked otherwise. Infiltration is caused by air leakages in the building envelope, and cannot be regulated or controlled by the occupant. The infiltration losses has decreased historically, due to construction of tighter buildings, but according to the report, all buildings within the time frame of this project has infiltration losses of 1.5 air changes per hour at 50 Pa pressure difference. This means a TABULA air exchange rate of between 0.1 and 0.2, according to Loga and Diefenbach (2012a).

The three main methods of ventilation are natural ventilation, mechanical ventilation, and balanced ventilation. Natural ventilation is based on thermal uplift and wind, and does not require any fans. Mechanical ventilation requires fans for moving the air through the building. This type of ventilation was common for apartment buildings from around 1970. Modern building make use of balanced ventilation, where a heat recovery unit recycles some of the heat from the outgoing air into the incoming air, making the energy need for heating smaller. Balanced ventilation can be controlled by the occupants in order to fit their needs. In the standard apartment buildings defined by Mjønes et al. (2012), the buildings constructed between 1981 and 2000 had mechanical ventilation, while those constructed between 2001 and 2010 had balanced ventilation with a heat recovery unit efficiency of 0.5.

2.2.5 Heating of direct hot water

Out of the energy consumption for an average Norwegian dwelling, 12 % is used for DHW (Bergersen et al., 2012). For a typical apartment block, the share is estimated to 30 %, including 5 % in losses from the storage tank (Hille et al., 2011). In Table A.1. in NS3031 (Standard Norge, 2011), the standardised yearly energy need for DHW in apartment blocks is given as 29.8 kWh/m^2, and the power demand is 5.1 kW/m^2. These values are used for several standardised energy calculations, but are not necessarily similar to actual values.

DHW in apartment blocks are generally heated by a shared water heater, and these are generally heated directly by electricity (Ulseth and Tjelflaat, 2013). As the losses from heat production by electricity are marginal, the efficiency of DHW heaters are determined by the heat losses from the storage tank (determined by the insulation of the tank) and the pipelines connecting the tank to the appliances (determined by the insulation and length of the pipes). The energy use will also depend on occupant behaviour, which is covered in Chap. 2.6.4.

Hille et al. (2011) states that a typical boiler in 1990 had a loss of 8.6 kWh/m^2·year, decreasing to 6.7 kWh/m^2·year in 2009. This decrease was caused by improved insulation of the tank, as well as a lower demand for DHW. However, the numbers are losses from the tank only, and for the smaller tanks typically used in single family dwellings.

The TABULA method requires values for heat loss from the DHW tank and distribution system, as well as the recoverable heat loss in order to calculate the total energy use. The only source that could be found for these values were those chosen for the TABULA energy calculations, gathered in a spreadsheet by Institut Wohnen und Umwelt GmbH (2013b). As Norway was not a part of the TABULA project, values for neighbouring countries are assumed to be the most accurate. However, the values for Sweden and Denmark were given for centralised systems only. Values for decentralised systems from various times of construction were provided for German example buildings, and these can be assumed to hold for Norwegian systems as well.[vi] The values are given in Table 7.

Table 7: Values for heating of DHW used for calculations of energy demands for systems with various ages. Gathered from German values used in the TABULA calculations (Institut Wohnen und Umwelt GmbH, 2013b)

		Installation year	
TABULA quantity [kWh/m^2·a]	TABULA explanation	Before 1994	1995
$q_{d,w}$	Heat loss of DHW distribution system	4.6	1.4
$q_{d,w,h}$	Recoverable heat loss of DHW distribution system	3	0.8
$q_{s,w}$	Heat loss of DHW storage	3.6	2.9
$q_{s,w,h}$	Recoverable heat loss of DHW storage	2.4	1.9

The exact development of DHW consumption is unknown, but it is believed that it increased significantly between 1960 and 1990, as a result of higher hygiene standards. Later years, the energy demand has possibly decreased, as a result of more dishwashers that heat the water themselves (Hille et al., 2011).

2.2.6 Other influences on the energy use

Hille et al. (2011) identified the most influential energy saving measures since 1990, apart from insulation, as the increasing use of heat pumps, reduced energy loss from firewood and oil burners, and a decrease in energy demand for heating of DHW.

In 1920, the average household would include 4.3 persons. This number had decreased to 2.3 in 2001. The area per person decreased between 1980 and 1989, but has later stabilised. The average area of buildings follow the same trend at first, but increase slightly after 1994 (Bøeng, 2005).

The average indoor temperature varies depending on the age of the apartment. Older apartments generally have a lower temperature, because the heat loss through the building envelope is greater, and the occupants do not want to spend as much money on energy. Additionally, the increased installations of central heating in apartments cause the apartments to be warmer due to not being as easily controlled by the occupants as electrical heating (Mjønes et al., 2012). The average indoor temperature is estimated to 22 °C by Mjønes et al. (2012).

2.3 Regulations

2.3.1 European regulations

Directive (EC) 2002/91 of 16 December 2002 on the energy performance of buildings, often referred to as The European Building Directive (EPBD) has been implemented in most of the

[vi] The DHW values used for the TABULA calculations vary significantly among the various countries, both for the values and the percentage of heat lost compared to the total heat production in the boiler. This could be caused by different systems or system definitions. As there is no background information on these numbers, picking the most appropriate value for Norwegian conditions is difficult. Therefore, picking the values connected to the country closest to Norway is possibly the best guess.

European countries, and it is also the basis for the Norwegian regulations on energy use in buildings (Husbanken, 2013). The directive lays down requirements regarding:

- Generating a general framework for a methodology for calculations of the integrated energy performance of buildings.
- Applying minimum requirements on the energy performance of new buildings and large buildings subject to major renovations.
- Energy certification of buildings.
- Regular inspection of boilers and air-conditioning systems in buildings, and an assessment of heating installations with boilers that are more than 15 years old.

The EPBD was revised, and the new requirements were published in 2009. These revisions involve that all buildings built after 2020 must be NZEBs, and new buildings occupied and owned by public authorities must be NZEBs after 2018. In addition, the energy used in the buildings must involve a substantial share of renewable energy (Husbanken, 2013).

The EPBD was fully implemented in Norway in 2010. As from that year, all Norwegian buildings must be certified through "Energimerkeordningen (translated: the energy grading arrangement) before they can be sold or leased to new tenants. This certification includes an energy labelling based on the calculated delivered energy (irrespective of energy carrier), using the standard NS 3031 (Standard Norge, 2011). The values are based on the necessary energy delivered to the air heater (calculated based on zero energy gains from solar transmittance and internal sources), plus a standard energy demand for lighting, equipment, and tap water heating of 28.9 kWh/m^2. The grading system goes from A to G, where C is based on the minimum requirements in the current technical regulation (Isachsen et al., 2011), while A is closer to a passive house. The grading requirements are collected in Tables 8 and 9.

Table 8: Energy grading from "Energimerkeordningen" as of 1.7.2013 (NVE, 2013). A = heated part of building related area [m^2].

	Maximum delivered energy [kWh/m^2·year]	
Building grade	Single housing	Apartment block
A	$85.00 + 800/A$	$75.00 + 600/A$
B	$115.00 + 1600/A$	$95.00 + 1000/A$
C	$145.00 + 2500/A$	$110.00 + 1500/A$
D	$175.00 + 4100/A$	$135.00 + 2200/A$
E	$205.00 + 5800/A$	$160.00 + 3000/A$
F	$250.00 + 8000/A$	$200.00 + 4000/A$
G	>F	>F

2.3.2 Norwegian regulations

The Norwegian government has not a set energy saving target for buildings. However, the last government declared a target of 15 TWh energy saved in buildings within 2020 (Ministry of Petroleum and Energy, 2012). Heating with oil boilers will be forbidden within 2020, according to report no. 21 to the Storting by the former Ministry of the Environment (2012). Areas used for calculations in the Norwegian regulations are based on BRA (available area), which simply put is the sum of all floor areas within the walls of the building. The details are covered in NS 3940 (Standard Norge, 2012).

Table 9: Energy grading from "Energimerkeordningen" as of 1.7.2013 (NVE, 2013) for the apartment blocks described in Table 1.

	Maximum delivered energy [kWh/year], sorted by construction year		
Building grade	1981-1990	1991-2000	2001-2010
A	82.89	83.70	83.45
B	108.16	109.49	109.08
C	129.74	131.74	131.13
D	163.95	166.88	165.99
E	199.47	203.48	202.25
F	252.63	257.97	256.34
G	>F	>F	>F

Norwegian authorities have set requirements to buildings for a long time. Presently, the conditions set by the standard Byggteknisk forskrift 2010 (TEK 10) must be met by all newly constructed buildings or buildings subject to major renovations. However, the requirements are not mandatory if the building has a lower net energy demand than 15 000 kWh/year or if the energy renovation leads to higher costs over the lifetime of the building (TEK 10, 2010). NS 3700 is completely optional. Earlier building standards are described in this chapter in order to establish the properties of typical building from various construction years.

Building properties such as U-values, total energy use, thermal bridging, etc. are to be calculated using other given standards in order to control if the building meets the requirements. Most of the calculation methods are covered in NS 3031. Here, detailed calculations of energy for air heating and cooling are given, along with a table for standardized data for calculating energy need for lighting, equipment and DHW. In Table A.1, the yearly net energy need is 11.4 kWh/m^2 for lighting, 17.5 kWh/m^2 for equipment, and 5.1 kWh/m^2 for DHW.

The regulations set standards according to building type, room type (especially relevant for ventilation), and the length of time it is expected for someone to stay inside of the room. The numbers presented below are selected for rooms in apartment blocks where people are assumed to stay for longer periods of time. Apartments in blocks are usually not very large, and are less likely to contain rarely used rooms. Special requirements for kitchens and bathrooms are not included in the following summaries.

The "Byggeforskrift" and TEK series

The regulation Byggeforskrift 1949 (1949) set requirements to insulation in new buildings by defining minimum λ-values. The Norwegian State Housing Bank, which financed 62 % of all new buildings between 1952 and 1964, defined a maximum U-value of 0.4 in walls and roof (Mjønes et al., 2012, p. 40).

Byggeforskrift 1949 was later replaced by TEK 69 (1969), where minimum λ-values for walls, roof and floor are defined, according to the expected air temperature of the room, as well as a maximum infiltration loss (4 air exchanges at 50 Pa).

Later updates (TEK 87 (1987), TEK 97 (1997), later updated as TEK 07 (Statens bygningstekniske etat, 2007), and TEK 10) set increasingly stricter demands for the maximum U-values. These are collected in Table 10.

The U-values from the TEK regulations in Table 10 do not necessarily need to be followed in order for a building to be approved. It can also be approved if the U-values of the construction parts are lower than some less strict U-values, and if the yearly energy demand for space heating

Table 10: Maximum U-values [W/m^2K] for apartment blocks specified by the TEK regulations and NS 3700 for passive houses.

	Maximum U-value [kWh/m^2]				
Regulation	Walls	Ceiling	Floor	Window	Door
TEK 87	0.30	0.20	0.3	2.4	2.00
TEK 97	0.22	0.15	0.15	1.60	1.60
TEK 07	0.18	0.13	0.15	1.2	1.2
TEK 10	0.18	0.13	0.15	1.2	1.2
NS 3700 *	0.18 (0.11)	0.13 (0.085)	0.15 (0.08)	0.8	0.8

*Described in next section. Median of typical U-values for passive houses (Table B.1 in NS 3700) is marked with parentheses.

per m^2 is lower than a certain limit. This can be calculated by Eq. 1 for TEK 97 and Eq. 2 for TEK 10.

$$\frac{Q_{H,nd}}{A_{C,ref}}\frac{kWh}{m^2} < 120 + \frac{1600}{A_{C,ref}} \tag{1}$$

$$\frac{Q_{H,nd}}{A_{C,ref}}\frac{kWh}{m^2} < 115 + \frac{1600}{A_{C,ref}} \tag{2}$$

For TEK 10 requirements, this means a maximum energy use for space heating of 77.35 kWh/m^2 for 1980 centennial buildings, 79.49 kWh/m^2 for 1990 centennial buildings, and 78.84 kWh/m^2 for the newest building cohort, based on the values in Table 1.

Maximum thermal bridging was set to 0.06 W/m^2 in TEK 07.

Specific requirements for ventilation were introduced in TEK 97. The maximum air exchange could not exceed 1.5 exchanges per hour. In TEK 07, a minimum air exchange value of 0.5 exchanges per hour was introduced. In older original buildings, the natural infiltration due to leakages through the building envelope is high, and this ensures most of the fresh air supply. As building regulations requires increasingly tighter building envelopes in order to minimize the heat losses related to infiltration, the air quality is no longer be satisfactory by default, and must be supplied through the ventilation system.

According to Mjønes et al. (2012, p. 52), early apartment blocks utilized natural ventilation, but this began to change in the 1970 centennial, as mechanical ventilation became increasingly more common. Mechanical ventilation allows for heat recovery, and TEK 97 set a requirement for the efficiency of the heat recovery unit of at least 70 %. This was later increased to 80 % in TEK 10.

TEK 97 also set some requirements to the heating source: Buildings constructed in areas with "tilknytningsplikt" (areas where buildings are required to be attached to the district heating system) must utilize energy from district heating. Also, "a significant part" (at least 40 % in TEK 10) of the energy for the building must be covered by other sources than electricity or fossil. Installing oil boilers for base load heating was forbidden by TEK 10.

NS 3700

The Norwegian standard NS 3700 (Standard Norge, 2013) was first published in 2010, and an updated version followed in 2013. It contains criteria for three different buildings: Class 1 low energy buildings, class 2 low energy buildings and passive houses. The standard is not mandatory, but it must be followed in order to approve a building as a passive house or low energy building. It is based on TEK 10, but with some extra demands. As low energy buildings are not relevant to the work of this project, only the requirements relevant for passive houses are covered here.

A passive house must satisfy both the maximum U-levels in Table 10 and the maximum air heating demand given in Eqs. 3 and 4, according to the average outside temperature. As there is no guarantee that the U-levels in Table 10 will result in a satisfactory energy air heating demand, the standard also adds a table of typical U-values for a passive house. The median of these values are marked with parentheses in Table 10.

If the average outside temperature $\vartheta_{ym} \geq 6.3$ °C, maximum energy use for space heating is:

$$\frac{Q_{H,nd}}{A_{C,ref}}\frac{kWh}{m^2} \leq 15 + 5.4 \cdot \frac{250 - A_{C,ref}}{100} \tag{3}$$

If the average outside temperature $\vartheta_{ym} < 6.3$ °C, maximum energy use for space heating is:

$$\frac{Q_{H,nd}}{A_{C,ref}}\frac{kWh}{m^2} \leq 15 + 5.4 \cdot \frac{250 - A_{C,ref}}{100} + \left(2.1 + 0.59 \cdot \frac{250 - A_{C,ref}}{100}\right) \cdot (6.3 - \vartheta_{ym}) \tag{4}$$

For Oslo climate ($\vartheta_{ym} = 6.3$ °C), this means a maximum energy use for space heating of 24.40 kWh/m^2 for 1980 centennial buildings, 24.77 kWh/m^2 for 1990 centennial buildings, and 24.67 kWh/m^2 for the newest building cohort, based on the values in Table 1.

Maximum heat loss by transmission and infiltration is 0.53 W/m^{2}K, and the thermal bridge values must be less than 0.03 W/m^{2}K. No energy for cooling is allowed.

Delivered electrical and fossil energy must be smaller than the total energy need minus 50 % of the net energy need for DHW.

2.4 Energy renovation

2.4.1 Strategies

SINTEF Byggforsk and the Norwegian State Housing Bank have developed a strategy for designing low energy buildings in Norway, called the Kyoto Pyramid. The pyramid defines the design steps that should be taken, and the optimal order of which they should be prioritised, in order to find the solution with the lowest possible environmental loadings, although not necessarily the most cost-efficient solution. (Andresen et al., 2008). The design process should follow the steps of the Kyoto Pyramid as depicted in Fig. 9, beginning at the bottom step.

Reduced heat conduction

Mjønes et al. (2012) suggest adding mineral wool as a standard insulation measure. If the buildings have an unheated attic, the insulation can easily be added to the attic floor. Similarly, insulation can be added to the basement ceiling, but special precautions must be taken in order to prevent humidity in the basement. In both cases, the room height will be reduced.

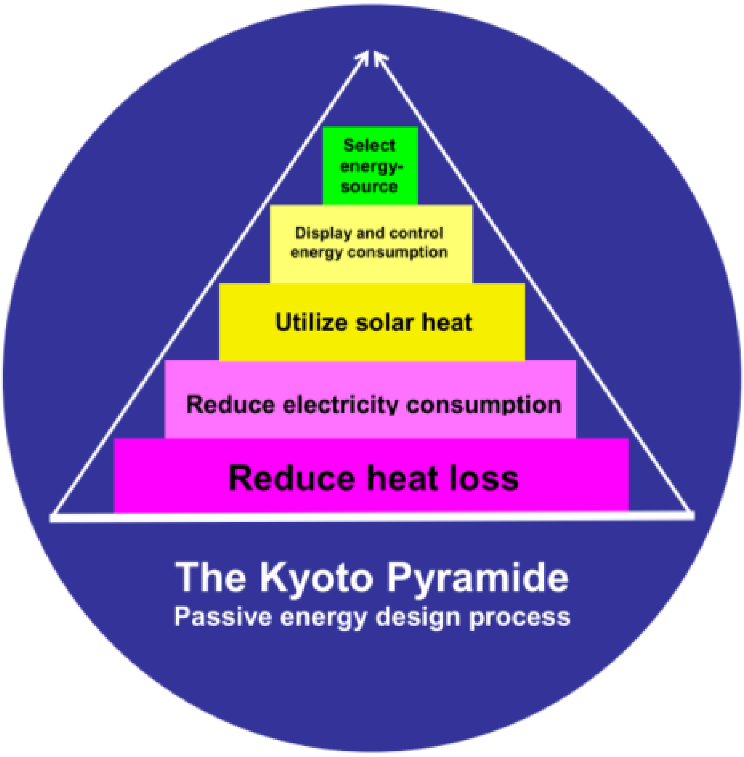

Figure 9: The Kyoto Pyramid for dwellings, describing the passive energy design process (Andresen et al., 2008).

Insulation can be added to either the inside or the outside of the wall, and the reduction of thermal bridging depends on this. If the insulation is added from the outside, the thermal bridging will be reduced, but it will stay almost unaffected if the insulation is added from the inside. Because of this, and additional problems such as reduced living area, insulation is usually added on the outside of the wall (Thue and Dalehaug, 2007). Aga (2013) simulated the thermal bridges in a similar wall with 100 mm insulation, and found the results to be 0.14 W/m^2K for the existing wall, and 0.05 for a wall insulated with 100 mm mineral wool on the exterior. This suggests that the thermal bridges can be greatly reduced when applying insulation on the outside of the wall. Techniques for retrofit insulation will not be described in this project.

Windows and doors can be replaced with units with higher U-value.

New heating source

There are several opportunities for upgrading the heating system with a new heating source. The most simple alternative for buildings without a centralised heating system are buying new electrical radiators, stoves for firewood, or air-air heat pumps. Other alternatives include district heating, centralised boiler, and heat pumps based on heating water (all of which require a hydronic heating system).

Smelhus (2014) stated that the currently most popular central heating option for apartment blocks is geothermal heat pumps. Where district heating is required, this is combined with a boiler for peak loads, usually fuelled by oil or electricity. Boilers running on solid fuels (such as pellets, wood chippings, firewood, etcetera) are often regarded as impractical for large buildings, as they require large areas and are laborious to operate.

As mentioned in Chap. 2.3.2, fuel oil must be replaced with alternate heating sources within

2020. This can be solved by simply using bio-oil instead, converting the boiler to another fuel (such as biomass or gas), or by replacing the boiler.

When choosing a heat pump, the local conditions should be evaluated in order to find the optimal heat pump technology. Heat can be collected from sea water or waste water if these sources are located nearby. Ground-source systems require large areas, and are usually not fit for urban environments, where apartment blocks normally are located. Geothermal heat pumps require a short distance from the surface to bedrock, and the heat conductivity of the bedrock can vary depending on its composition. Ground-source and geothermal heat pumps can also be utilised for cooling in the summer, by extracting the frigidity stored in the ground or rock.

System efficiencies for relevant heating sources from NS 3031 are gathered in Table 11. The standard also sates "regulation efficiencies", which account for some of the heating sources being less smoothly regulated as others, resulting in a higher energy output and indoor temperature than necessary at times.

Table 11: System efficiencies for equipment from 2007, as defined in NS 3031 (Standard Norge, 2011). Values for radiators are chosen for centralised heating systems.

Heating source	Production efficiency	Energy transfer efficiency	Regulation efficiency
Wood stove	80 %	100 %	80 %
Centralised boiler for biomass (wood, pellets, chippings)	85 %	95 %	95 %
Heat pump, air-air	240 %	100 %	95 %
Centralised heat pump, ground/water-water	250 %	95 %	95 %
District heating	98 %	95 %	95 %
Direct electricity with thermostat	100 %	98 %	100 %
Electrical boiler	98 %	95 %	95 %
Centralised gas boiler	90 %	95 %	95 %
Centralised fuel oil boiler	85 %	95 %	95 %

Energy rehabilitations may also be conducted based on a desire to limit emissions. CO_2 emissions for various heating sources are collected in Table 12. The emission values are based on LCAs of the various energy sources, where emissions connected to production and transportation are included. The electricity mixes include emissions from imported electricity, and are based on average values from 2007-2011. District heating emission values are collected for 2007-2010 (CICERO et al., 2012).

It is clear from the table that geothermal heat pump is the alternative with lowest emissions, and this holds for all electricity allocation cases.

Other aspects

The heat recovery systems can be improved by installing or replacing a heat recovery unit. According to Mjønes et al. (2012), typical present apartment blocks have a heat recovery unit efficiency of 0.7.

Enova (2004) states that infiltration losses are difficult to calculate, and that extensive measuring is required in order to find the real infiltration losses. The manual provides instead

Table 12: CO_2 emissions for various heating sources in g/kWh delivered to building heating system, sorted by base emissions per unit and emissions for one unit of delivered energy from CICERO et al. (2012), when dividing by efficiencies in Table 11. Emissions for biogenic sources are used for wood and pellets.

	CO_2 emissions [g/kWh]	
Energy carrier	Per unit	Divided by efficiencies
Electricity, Norway	50	51.02
Electricity, Nordic mix	200	204.08
Electricity, EU27	542	553.06
Oil	309	401.30
District heating*	245	278.41
Firewood (stove)	261	407.81
Pellets or wood boiler	261	338.96
Air-air heat pump, Norway	50	23.15
Air-air heat pump, Nordic	200	92.59
Air-air heat pump, EU27	542	250.93
Geothermal heat pump, Norway	50	22.52
Geothermal heat pump, Nordic	200	90.09
Geothermal heat pump, EU27	542	244.14

*Based en economic allocation

infiltration values for various locations. For the standard places with moderate wind, the infiltration loss is given as 0.15 h^{-1}, and this is also the value chosen by Mjønes et al. (2012) for all building calculations.

Solar collectors can be installed on the roof, and can cover about 50 % of the energy need for DHW (Hille et al., 2011). The DHW tank and system can be upgraded in order to reduce heat leakages. Solar energy can also be utilized for electricity production by installing photovoltaic (PV) panels.

Room heating and electricity can share heating sources in buildings with hydronic heatings systems, such as boilers with two-stage heating. In order to limit the scope of the project and simplify the energy and cost calculations, these systems will not be considered further. However, these solutions are likely to result in a lower energy demand than the results in this project, and also might be a cheaper rehabilitation alternative, as fewer boilers are needed.

Lindberg and Magnussen (2010) evaluated several other aspects for renovation, such as saver shower, energy follow-up, separate billing for DHW, and several types of energy automation, but these are not included in this project, as they are closely related to user behavior.

2.4.2 Previous renovation measures

Hille et al (2011) identified the most influential energy saving measures since 1990, apart from increased insulation, as the increasing use of heat pumps, reduced energy loss from firewood and oil burners, and a decrease in energy demand for heating of DHW.

Some of the apartment blocks from 1981 or later have undergone refurbishment measures. The extent of this is given in Table 13.

Looking further into the renovation values from Mjønes et al. (2012), it is clear that the energy renovation is even smaller than what is implied by the values in Table 13. The renovation mea-

Table 13: Share of Norwegian apartment subjected to renovation measures, sorted by construction year and type of renovation (Mjønes et al., 2012).

	Construction year		
Renovation type	1981-1990	1991-2000	2001-2010
None	91 %	97 %	100 %
New windows	7 %	3 %	0 %
Added insulation, walls	5 %	3 %	0 %
Added insulation, ceiling / floor	6 %	0 %	0 %

sures applied to the buildings originating from 1991-2000 do not increase the energy standard of the building, except for 1/3 of the window replacements, where the standard is increased to the newest level. The other renovations could be linked to maintenance, or simply less ambitious energy efficiency measures.

For the oldest buildings, all the additionally insulated walls, ceilings, and floors were upgraded to the newest standards, while the windows had been upgraded to 1, 2, and 3 % out of the total 6 % for the oldest, medium, and newest building standard, respectively. Average life time of windows were a little more than 30 years. 91 % of the buildings constructed between 1981 and 1990 have not been subject to any energy related refurbishment, and this number is even higher for newer buildings (Mjønes et al.)

2.4.3 Saving potential

Thyholt et al. (2009) calculated the energy saving potential for two different renovation strategies: One moderate (around 10 cm retrofit insulation on the building envelope, windows with U-value of 1.2 W/m^{2}K, and air leakages of 3.0 h^{-1}) and one ambitious (around 30 cm insulation, windows with U-value of 0.7 W/m^{2}K, air leakages of 1.5 h^{-1}, and balanced ventilation with 70 - 75 % heat recovery). After a moderate renovation, the energy consumption in apartment blocks constructed between 1981 and 1990 decreased (from around 140 to around 130 kWh/m^2), but the change was low compared to other building types and construction years. For the same building type, the energy consumption after an ambitious renovation was at the same level as for the original building, while this rehabilitation resulted in energy consumption below that of the moderate rehabilitation for all other buildings. The energy saving potential for buildings constructed between 1991 and 2005 were not evaluated, as it was assumed that these building were in fairly good condition, and that energy related measures were not likely to be carried out as part of a renovation.

Following the calculations by Mata et al. (2013a), the greatest energy saving potentials for the Swedish residential sector involve heat recovery systems, ideally in a combination with slight reduction in the indoor temperature. However, this is not necessarily the case for Norwegian buildings, because of the different standard heat delivery systems. Mata et al. (2013a) concluded the potential energy in the Swedish residential sector had a total reduction potential of 55 % when applying all energy savings measures evaluated.

Pauliuk et al. (2013) calculated the energy demand in renovated buildings based on construction year and building type. Original apartment blocks had a yearly energy demand for heating of 71 kWh/m^2 and 58 kWh/m^2 for buildings constructed 1981-1990 and 1991-2010, respectively. After applying renovation package 1 (as described in Table 14), the yearly energy use for heating was calculated to 29 kWh/m^2 for the oldest and 28 kWh/^{2} for the newest buildings. Renovation package 2 resulted in 11 kWh/m^2 for both building types.

Table 14: Overview of building properties for original or rehabilitated buildings (Pauliuk et al., 2013)

Parameter	Package I	Package II	Standard, detached and blocks	Passive houses
Wall	Add 150 mm mineral wool	Add 250 mm mineral wool	0.18 W/m^2K	0.15 W/m^2K
Ceiling	Add 150 mm mineral wool	Add 250 mm mineral wool	0.13 W/m^2K	0.13 W/m^2K
Floor	Add 100 mm mineral wool	Add 200 mm mineral wool	0.15 W/m^2K	0.15 W/m^2K
U-values windows [W/m^2K]	1.2	0.8	1.2	0.8
Thermal bridges [W/m^2K]	0.07	0.05	0.06	0.03
Air tightness, h at 50 Pa	0.4	0.7	0.7	1.7
Ventilation heat recovery [%]	70	80	70	80

2.5 Economic aspects

2.5.1 Past studies

In order to predict the future development of the building stocks, costs must be taken into account. The project thesis conducted for this master thesis only took the reduced energy demand into consideration when evaluating the renovation measurements. In most cases, economy is the determining factor when choosing when and how to conduct a renovation.

Price development of energy carriers affects the preferences for heating sources, although only in a long-term perspective (Hille et al., 2011). Development for some relevant energy carriers are gathered in Fig. 10.

The report by Mjønes et al. (2012) contains calculations of the economic savings of some renovations strategies on apartment blocks, when reaching the TEK 10 targets. No energy renovations were found to be profitable for apartment blocks constructed after 1970, but retrofit insulation and air-air heat pumps could be profitable for older apartment buildings.

Rambøll and Xrgia (2011) found that the greatest economic rehabilitation potential for Norwegian apartment blocks are in heat recovery, and somewhat in replacing windows and doors. Total rehabilitation costs for apartment blocks were found to be 800 NOK/m^2 for passive standard, 530 NOK/m^2 for TEK 10 (p. 33), which means around 1.400.000 NOK and 900.000 NOK, respectively, for the building cases in this project.

Førland-Larsen (2012) researched the effects of improving building components (windows, outer walls, pumps, fans, ventilation system, artificial lighting systems, and energy management systems) by renovation or replacement in Norwegian buildings. In general, the chosen upgrades for heat recovery systems, fans, and lighting systems were profitable. The most profitable energy efficiency measure was replacement of windows - even when the replacement windows had U-values much lower than the TEK 10 requirements. Additional insulation of walls, roofs, and floors to TEK 10 standard were not found to be profitable.

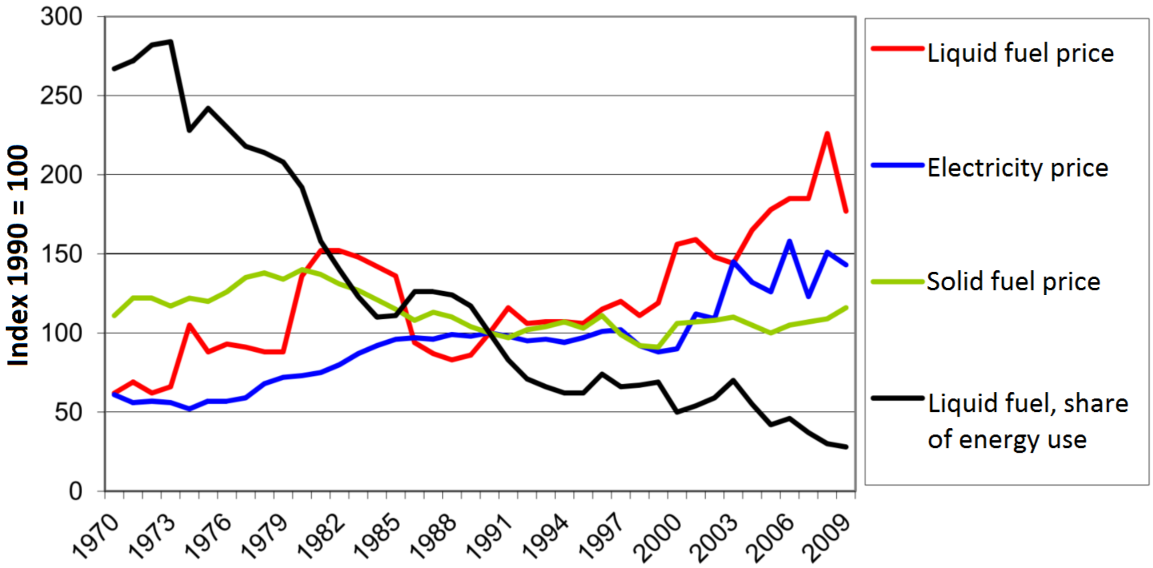

Figure 10: Price development for various energy carriers in Norway, and development of solid fuel consumption in dwellings. Given relative to situation in 1990, for the years 1970-2009 (Hille et al., 2011).

Lindberg and Magnussen (2010) evaluated costs for energy savings measures in the existing Norwegian dwelling stock as part of the Klimakur 2020 initiative. A large number of energy efficiency measures were considered, and sorted in the groups: Energy follow-up, insulation and tighting, technical equipment, energy control, and the costs of reaching low energy levels as defined in NS 3700. The most cost-efficient solutions were simple energy follow-up by janitor, followed by increased air-tighting by sealing the air gaps. The least cost-efficient alternatives were installation of heat recovery units and retrofit insulation of exterior walls.

Results from various rehabilitation cost studies were gathered by Kalhagen et al. (2011), and based on an evaluation of the reports, the additional costs of average energy rehabilitations in dwellings were se to 1000 kr/m^2 for low-energy rehabilitations, 1800 kr/m^2 for passive house rehabilitations, and 1250 kr/m^2 for NZEBs. However, the report points out that the costs are likely to decrease by 25 % within 2020, and 50 % within 2040. Based on net present value[vii](NPV) calculations of buildings with a discount rate of 7 % and the time frame 2011-2039, none of the rehabilitation alternatives were found to be profitable. However, the values were based on the total existing Norwegian dwelling stock, and so the results are not necessarily valid for newer apartment blocks.

Dokka et al. (2009) calculated the payback period for low energy dwellings in general to 22 years, or 11 years if 40 % of the additional costs are covered by the government. The payback periods of passive houses and low energy dwellings were 12 years and 6 years, respectively. These results were based on energy costs of 0.9 NOK/kWh and a discount rate of 4 %.

Arnstad (2010) estimated that simple energy rehabilitations would have additional costs of 400 kr/m^2, rehabilitation to low energy buildings 1500 kr/m^2, and passive houses 1800 kr/m^2.[viii]

[vii]Described in Chap. 3.4.
[viii]More on the definitions in Table 17

2.5.2 Public funding schemes

Husbanken

Husbanken (The Norwegian State Housing Bank) can provide loans or funding for rehabilitation projects if the goal is increased accessibility for elders or physically disabled, or environmental purposes (such as lower energy demand). However, the funding will not support the rehabilitation itself, but rather the evaluation in order to choose the best rehabilitation measure (Husbanken, 2014). As loans or the costs of planning are not included in this project, support from Husbanken will not be considered further.

Enova

Enova is a public enterprise owned by the Norwegian Ministry of Petroleum and Energy. Its main support program for reduced or greener energy in existing buildings are the programs for heating centrals and the program for support for existing buildings.

The programs for heating centrals are divided into a simple and an extensive program. The simple program is designed for energy rehabilitation measures by building owners. The measures covered are described in Table 15. The maximum support is, however, also limited to maximum 200,000 NOK for the entire project and maximum 40 % of the total additional investment costs (Enova, n.d.-b).

Table 15: Maximum available support through the Enova simple support program for heating centrals, sorted by heating technology and buildings constructed comprised by TEK 10 regulations (Enova, n.d.-b).

	Maximum support	
Heating source or fuel	Existing buildings	TEK 10 buildings
Wood chippings	1700 NOK/kW	600 NOK/kW
Briquettes	1700 NOK/kW	600 NOK/kW
Pellets	1700 NOK/kW	600 NOK/kW
Heat pump, air-water	1100 NOK/kW	No support
Heat pump, liquid-water	1600 NOK/kW	500 NOK/kW
Solar collector	201 NOK/m^2	201 NOK/m^2

If the planned energy renovation project falls outside the definition of the simple support program, it might be covered by the extensive support program (Enova, n.d.-c) or the program for support for existing buildings (Enova, n.d.-d), depending on whether the applicant is a private individual or a company. However, the support distributed by these programs cannot be calculated in a simple way, such as for the simple program. Some of the criteria for receiving support from the program for support for existing buildings are that the energy must be reduced by at least 10 %, and that it must fulfil the criteria for passive houses or low-energy houses class 1 from NS 3700. Air-air heat pumps or internal heat distribution system (unless replacing direct electricity with district heating) are not covered (Enova, n.d.-d).

Enova does not provide a set amount of support for various project, but rather calculates the support individually based on project applications. It has not been possible to obtain a typical support value for the example buildings in this project, but the support from Enova can be substantial. In the case of rehabilitation of Myhrerenga housing cooperative, Enova provided 6 million NOK for the project, which accounted to about 30 % of the additional costs for energy rehabilitation (SINTEF Byggforsk and NTNU Samfunnsforskning, n.d.).

2.6 Predicted development

2.6.1 The building stock

Kalhagen et al. (2011) sums up expected renovation and demolitions rates for Norwegian dwellings from various reports. Demolition rates are set to 0.6 % for dwellings, which results in a lifetime of 167 years. The renovation rate is commonly set to 1.5 %. Arnstad (2010) set a specific rehabilitation rate for energy rehabilitations at 2.0 % in their report. The predicted development in building area by Kalhagen et al. (2011) is visualised in Fig. 11. The building area is expected to continue to grow, as the increase in new building area will outweigh that of the demolished buildings.

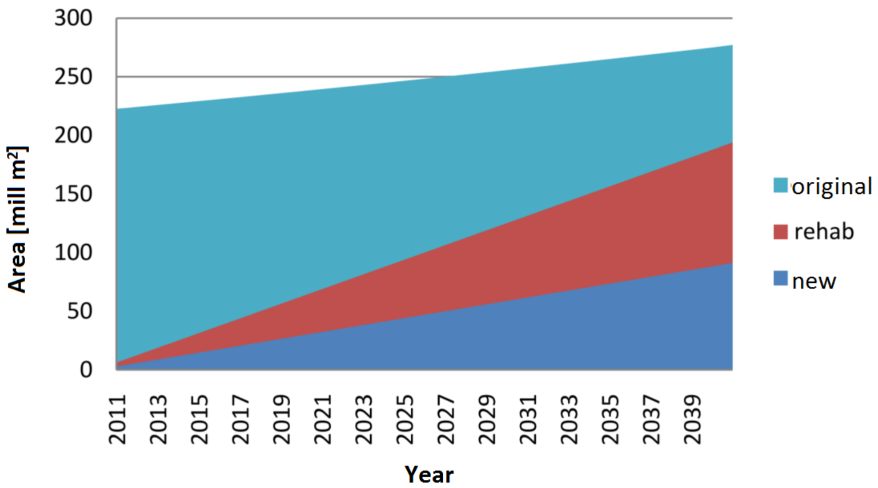

Figure 11: Predicted total area of Norwegian dwellings, 2011-2039, sorted by existing buildings in their present state (original), existing building subject to rehabilitation (rehab), and new buildings (Kalhagen et al., 2011).

Hille et al. (2011) criticise the demolition value of 0.6 % as being too high, based on previous demolition rates. Instead, a demolition rate of 0.1 % is used for predicting the building mass and energy demand. When assuming a population increase of 27 % from 2010 to 2030, the building stock could increase by 27 - 90 %, depending on the growth in area per person (tested: 0 - 2 %). This means between 75 and 207 million m^2 of new building area.

Sartori et al. (2008) developed a dynamic model of the Norwegian building stock, based on a dynamic material flow analysis (MFA). The input data are population, area per person, lifetime of building, new buildings, and renovation rate. The scenarios investigated are visualised in Figs. 12 - 14. Renovation and demolition activity were based on normal distribution functions. With inputs corresponding to the scenario labeled as medium, the model predicts a total area of around 345 million m^2 in 2050 and 396 million m^2 in 2100.

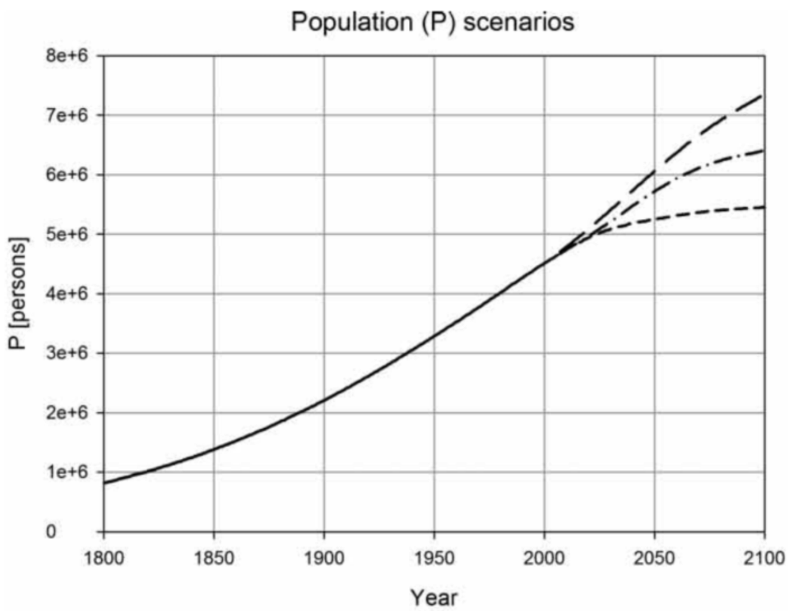

Figure 12: Previous development and scenarios for the Norwegian population 1800-2100 (Sartori et al., 2008).

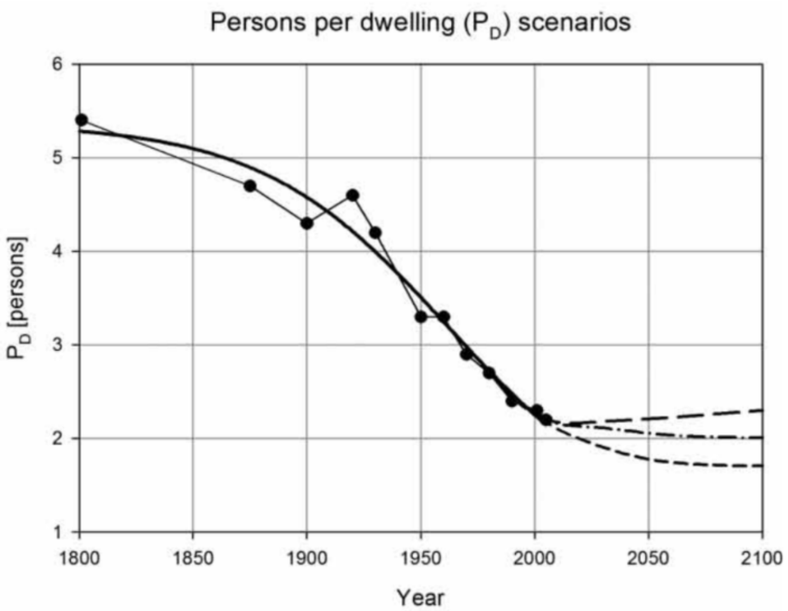

Figure 13: Previous development and scenarios for amount of persons per dwelling in Norway 1800-2100 (Sartori et al., 2008).

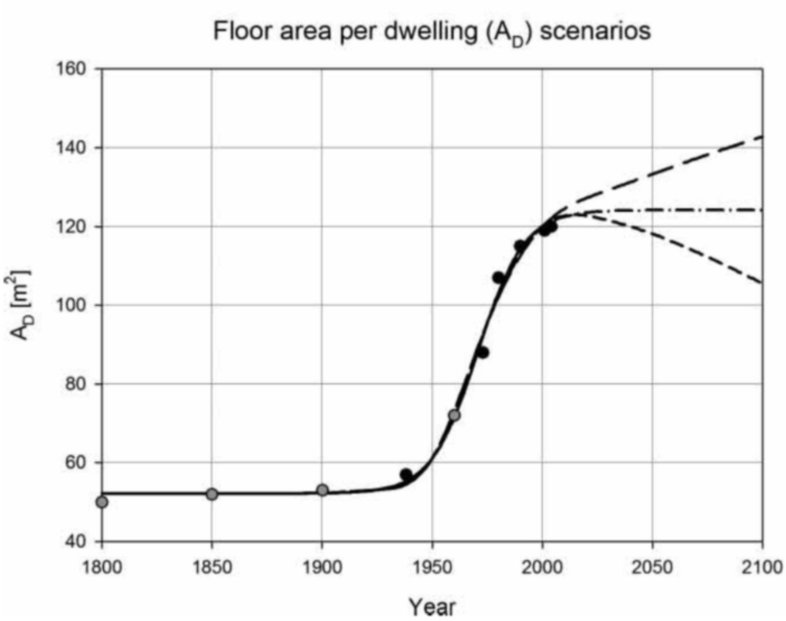

Figure 14: Previous development and scenarios for floor area per dwelling 1800-2100 (Sartori et al., 2008).

Sandberg et al. (2014) adapted the model further, allowing among other adjustments, for separating the building stock into construction years and building types (compact and detached houses), choosing normal or Weibull distribution for the renovation and demolition rate, and producing outputs in number of buildings instead of building area. Setting the average lifetime of buildings to 125 years, the resulting dwelling stock results in the values shown in Fig. 15, where the results are compared with statistical values.

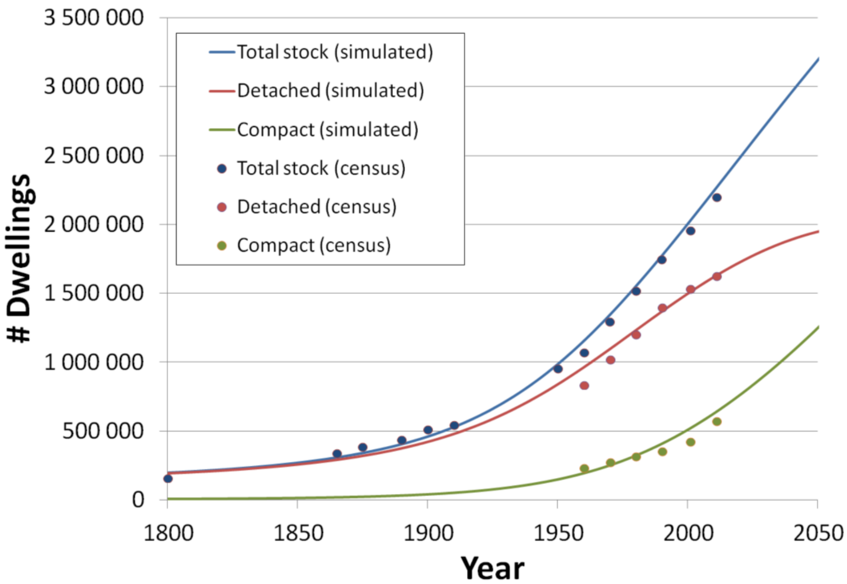

Figure 15: Norwegian dwelling stock demand between 1800 and 2050, total and in types, simulated using smooth input curves. Compared with statistical data on dwelling stock size (Sandberg et al., 2014).

Mjønes et al. (2012) developed a prognosis for apartments constructed between 2010 and 2020. The values are gathered in Table 16.

Table 16: Predicted development of the Norwegian apartment building stock 2010-2020, sorted by demolished, new, and total existing buildings (Mjønes et al., 2012)

Apartment type	Area [m^2]	Amount
Total demolished / vacated	1 354 424	19 170
Total new	10 130 536	143 624
Total existing	50 902 913	718 052

2.6.2 Residential energy demand

Hille et al. (2011) defined these nine factors as the main drivers for Norwegian energy use: Technological development, resident lifestyle and behaviour, population, technical building standard, building design, building size, regulations, public funding schemes, and energy taxation. They also evaluated the impact of the outdoor temperature on the energy demand. The energy consumption for heating in apartment blocks constructed before 2009 were predicted to decrease from 94.3 kWh/m^2 in 2010 to 81 kWh/m^2 in 2030.

According to Langseth et al. (2014), policy makers have stated that new building regulations in 2015 will be based on passive house energy levels.

Arnstad (2010) set an energy reduction target for the Norwegian building stock of 10 TWh/year by 2020 and 40 TWh/year by 2040. This is the half of the present energy consumption. Dwellings (including new buildings in the future) are calculated to have a total energy reduction potential of around 25[ix]TWh/year in 2040. Table 17 shows the renovation strategies used as a basis in the report for achieving this target.

Table 17: Renovation strategies for Norwegian dwellings, in order to reduce the total energy in dwellings to around 25 TWh/year. Sorted by year of renovation and based on energy consumption in original buildings of 201 kWh/$m^2\cdot$ year (Arnstad, 2010).

Year	Renovation	Energy consumption [kWh/$m^2\cdot$ year]
2015-2020	75 % low-energy, 25 % conventional	95 / 160
2020-2025	passive house	70
2025-2030	NZEB	55
2030-2040	one level above NZEB	30

Kalhagen et al. (2011) based the energy demand after renovation on the same values as Arnstad (2010), but adjusted consumption in NZEBs to 60 kWh/$m^2\cdot$ year. Energy scenarios were defined in order to predict the effects of building standards on the total future energy consumption. For rehabilitation of dwellings, 20 % of existing buildings are assumed to be rehabilitated between 2011 and 2040. The 0-alternative involves rehabilitations similar to average rehabilitations in 2011, alternative 1 and 2 involve that all dwellings are rehabilitated to low energy level in 2016 and 2013, respectively, passive house level in 2021, and energy efficient component and building parts in 2016. With these assumptions, the energy consumption for new or rehabilitated buildings will be similar to Fig. 16. The resulting energy consumption is based on alternative 1 an 2, the energy reduction potential for dwellings was estimated to 9 or 10 TWh/year in 2040.

Three renovation cycles were explored and modelled with a normal probability function by Sandberg et al. (2014): renovation cycles with average time between renovations of 20, 30 and

[ix] Values for residential and non-residential buildings seem to be switched for Table 7 and Figure 2 in Arnstad (2010). The values are similar, but not identical, and an approximate is therefore used here.

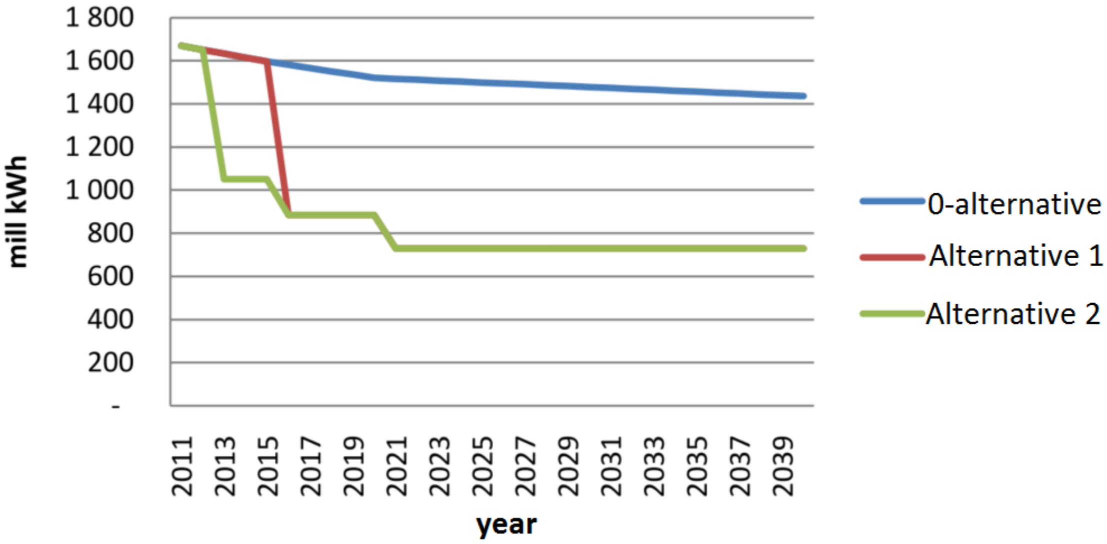

Figure 16: Predicted energy consumption in the Norwegian building stock for buildings rehabilitated or constructed the same year, 2011-2040. Sorted by energy consumption alternatives (Kalhagen et al., 2011).

40 years, respectively. The 20 year cycle is exemplified as replacement of components, the 30 year cycle as replacement of construction elements as windows or roofs and the 40 year cycle represents deep renovation of façades.

Sandberg and Brattebø (2012) compared their study with others on the field. Their most optimistic scenario resulted in 20 % energy increase in the dwelling sector. In comparison, the results from Sartori et al. (2009) varied between 6 and -23 %, and Thyholt et al. (2009) between 18 and -5 % for the time period 2005-2035. The Climate and Pollution Agency (2010) estimated an increase of 1.3 % from 2007 to 2020.

2.6.3 Heating sources and greenhouse gas emissions

Lindberg and Magnussen (2010) conducted a small sensitivity analysis on how energy costs could affect the chosen energy source in the future. However, the results are based on socio-economic costs. The cheapest alternative for replacing electric boilers in dwellings was district heating or pellets boiler. For dwellings with electric radiators, the best alternatives were air-air heat pumps, followed by pellets heaters. Installing hydronic heating is expensive, but if done, the cheapest heating alternative is district heating. Electricity-based energy sources will be the cheapest alternative, even with an increased electricity cost, although the report does not mention how large this increase is. Biomass alternatives are considered relatively costly in this analysis, as particle pollution contributes to high socio-economic costs. Future emissions from the building stock were also calculated in the report, but with the CO_2 emissions related to biogenic energy and electricity defined as 0. With these definitions, the report concluded that the Norwegian building stock could decrease its emissions from 1.6 megatons CO_2 in 2007 to 1.3 megatons in 2020.

Kalhagen et al. (2011) predicted the energy sources for low-energy buildings to be as in Table 18.

Pauliuk et al. (2013) based their calculation on the energy source distribution in buildings from 2010. The scenarios were combined with various rates of rehabilitation and demolition. With

Table 18: Average predicted energy mix for low-energy building types (Kalhagen et al., 2011).

Heating source	Low-energy	Passive	nZEB
Electric boiler	10 %	8 %	10 %
Electric radiator	18 %	22 %	9 %
District heating	18 %	19 %	6 %
Wood stove	13 %	4 %	5 %
Other biomass stove	8 %	2 %	5 %
Biomass boiler	8 %	22 %	19 %
Heat pump, water/air-air	13 %	11 %	28 %
Heat pump, air-air	11 %	9 %	13 %
Solar collector	0 %	3 %	5 %

a baseline of 0.6 % demolition and 0.5 % renovation, total CO_2 emissions from the Norwegian building stock were reduced from 8.7 Mt/year in 2000 to 7.8 Mt/year in 2050. For the most optimistic scenario, the emissions were reduced to 2.0 Mt/year.

Graabak and Feilberg (2011) based their predictions on emissions from European electrical power plants on the prices of CO_2 quotas. They predicted that the efficiencies of both lignite, coal, gas, oil, and biomass technologies would increase with about 30 %. They combined these with CO_2 equivalent emission factors from 2005 for European power plants and their predicted quota prices for the four scenarios in order to predict the future composition and emissions of the European energy mix. The scenarios are described in Fig. 17, and the related GHG emissions are collected in Table 19.

Table 19: Predicted development of GHG emissions in CO_2 equivalents for European electricity (Graabak and Feilberg, 2011)

	Yearly GHG emissions [g CO_2-eq./kWh]			
Scenario	2010	2030	2040	2050
Red	361	284	271	258
Yellow	361	233	211	192
Green	361	223	187	157
Ultra Green	361	196	113	31
Blue	361	183	136	114

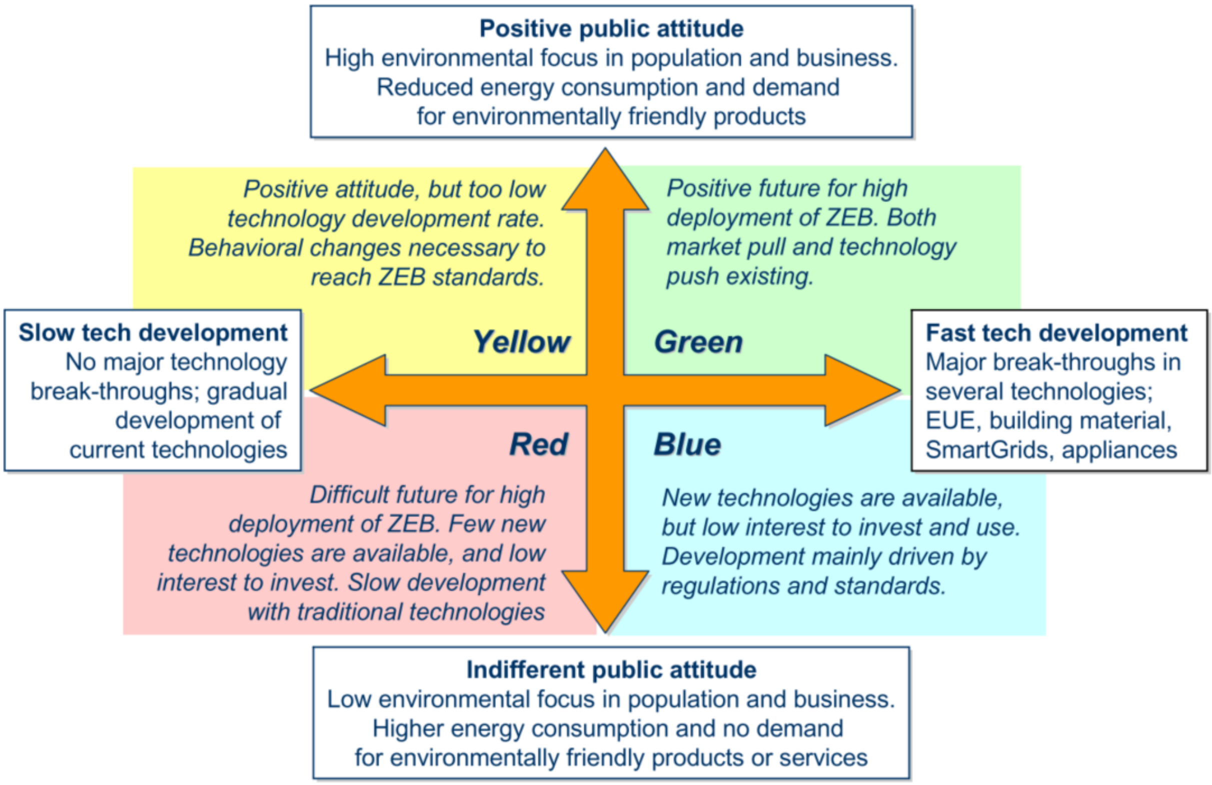

Figure 17: The different storylines for the emission scenarios by Graabak and Feilberg (2011).

Sandberg and Brattebø (2012) predicted the future GHG emissions from the Norwegian building stock, varying the electricity mixes. For all scenarios, the yearly emissions begin at 2.3 million tons CO_2 equivalents and are expected to increase at first, then to decrease until 2050. When basing the calculations on Norwegian electricity mix, the emissions in 2050 are slightly increased to 2.4 million tons CO_2 equivalents, while Nordic mix results in 3.4 million tons CO_2 equivalents. It is pointed out that the actual emissions are more likely to be somewhere in between when import and export are being accounted for. The third alternative was based on Norwegian emission data for energy demand not exceeding today's level and marginal technologies based on the work by Graabak and Feilberg (2011), and this resulted in an energy demand of 3.7 million tons CO_2 equivalents in 2050. The results from this alternative is shown in Fig. 18. Emissions from sources other than electricity are constant for all alternatives.)

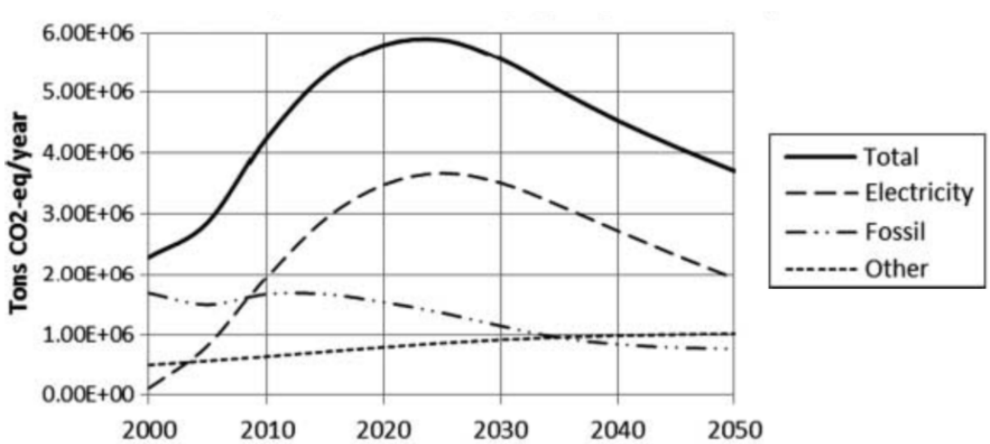

Figure 18: Predicted GHG emissions from the Norwegian dwelling stock for the alternative energy carriers (Sandberg and Brattebø, 2012).

2.6.4 Occupant behaviour

The future profits from energy efficiency are highly related to the energy prices. The last ten years, increased energy prices have caused energy efficiency in Norway to be 30 % more profitable today than in the 1990 centennial (Norsk teknologi, 2013).

Bergersen et al. (2012) point out that occupants in apartment blocks with shared energy measuring devices for energy are likely to use more energy, as they do not see the benefits of adjusting their consumption.

Smart meters for detailed measuring and control of electricity consumption are to be installed in all Norwegian dwellings within 2019. This will make it easier for the inhabitants to control and reduce their electricity demand (Langseth et al.). To the author's knowledge, no studies have been conducted on the impact of smart meters on energy consumption for heating in building.

According to Hille et al. (2011), occupants who install heat pumps often choose to keep a higher indoor temperature and to heat a higher number of rooms. In the end, energy consumption depends on the occupants' knowledge, attitudes, and preferences. Increased wealth leads to a slight decrease in energy consumption per m^2, but this is counteracted by a higher increase in area (Hille et al., 2011). There are indications of the indoor temperature having increased last years. The DHW demand is subject to change depending on the inhabitants' hygiene preferences.

Rehabilitations of apartments in building co-operatives must be approved by 2/3 of the general assembly if they are to be implemented. This is not an easy decision to make for the occupants, as the rehabilitations represent a major investment. Whether the measures will be carried out depends heavily on the information provided by the board, as many occupants, especially elderly, have difficulties understanding the rehabilitation measures and benefits. The information will be based on pre-projects carried out by external companies. When a dwelling is owned by someone else than the occupants, the owner is likely to pay no attention to energy renovation, as long as the occupants pay the energy costs and the quality of the dwelling is similar to the alternatives (Thyholt et al., 2009).

3 Method

3.1 Goal and scope

Properties of typical Norwegian apartment blocks built in the time frames 1981-1990, 1991-2000, and 2001-2010 are defined in order to simulate the energy use of these buildings in their original conditions. Renovation packages based on the TEK 10 and passive house standard are defined for each buildings, and different combinations of these packages will be applied to the test buildings in order to track the energy savings connected with the various renovation measures.

Then, cost analyses will be performed based on the energy consumption found from the energy balance calculations, in order to find the most profitable renovation strategies for the building inhabitants in the different standard buildings.

The energy and cost savings of the different measures should give an inclination as to which energy rehabilitation measures will be popular in the future. Scenarios for the chosen buildings will be simulated for the time span 2014-2050, in order to compare the effects of different renovation on the aggregated energy use and CO_2 emissions. The scenarios will not be an attempt at predicting the future, but rather to investigate various possibilities regarding the priorities of the inhabitants (economy vs. enery saving) or future regulations.

Electrical appliances and lighting will be excluded from the calculations. The buildings will be based on typical, as opposed to average, properties. This will be the most realistic approach for the initial energy balance calculations and cost calculations, but not when calculating aggregated energy use and emissions. All simulations will be based on the Oslo climatic zone, which is defined in NS 3031 as standard reference climate.

3.2 The energy balance

In this case study, typical Norwegian apartment blocks will be selected for different time frames, and be subject to combinations of different renovation strategies in order to examine the typology characteristics and changes in energy balance factors. The typical values are found through literature, and the final values will be calculated using the TABULA method mentioned in chapter 2.1.2. App. A.1 contains an excerpt of all values needed for the calculation. App. A.3 contains the equations used for the calculations.

No Norwegian institution took part in the TABULA project, and as a result, Norwegian typologies have not been defined yet. However, some Norwegian values have been chosen for the EPISCOPE project (Institut Wohnen und Umwelt GmbH, 2013b). As a result, typologies have to be made specifically for this project in order to complete the necessary calculations.

Net useful energy for room heating will be presented following the calculations. All calculations are based on Oslo climate.

In order to better understand and simplify the TABULA calculation method, a worksheet has been made in Microsoft Excel for all calculations done in this project. This worksheet and instructions for using it is delivered electronically with the project in App. D. The calculations in the worksheet follow the TABULA method, with a few exceptions: The $R_{measure}$ values are set to 0. Instead of adding R-values from the refurbishment measure to the original R-value, the R_{total} values are changed to a final value defined by the Norwegian standards.

Some equations are not properly defined in the TABULA Calculation Procedure (Loga and Diefenbach, 2012a), as their denominations either makes little sense or do not match up in the equations. In these cases, assumptions have been made as to how these equations probably should be. Energy use for cooling purposes is not included by TABULA, and is therefore not included in this project either.

Renovation projects

As the vast majority of the building stock relevant to this project has not been subject to energy refurbishment, the original state of the sample buildings are based on the condition of which they were built. Mjønes et al. (2012) provide extensive information on the typical historical buildings, sorted into time frames of ten years at a time, and this project will use these same time frames in order to classify the renovation typologies. If the necessary values are not found in the report by Mjønes et al. (2012), the numbers will be based on minimum values in the relevant regulations, other sources, or assumptions.

The renovation strategies will be based on Norwegian requirements (TEK 10 and passive house, as defined by NS 3700), as well as common renovation strategies by today's technology. The reasoning behind all values chosen is described in detail in the following chapters, and a full summary of the values chosen for calculation will follow later in this chapter.

This report will not calculate whether the buildings actually qualify as passive houses or not, as this would require extensive calculations in accordance to several Norwegian standards.

Heating and ventilation

When running the calculations in the Excel sheet, only the required energy input for room heating will be calculated. An evaluation of energy sources for room heating and their various efficiencies will be done afterwards, as described in Chap. 3.3. All efficiencies are therefore temporarily set to 1.

DHW properties are based on the values in Table 7. Buildings constructed before 1990 are assumed to have the properties of the DHW systems built before 1994, while all other buildings, including the rehabilitated ones are assumed to have a DHW system with the properties of the systems from 1995 or later. The energy demand is assumed to be 30.0 kWh/m^2 (Mjønes et al., 2012). The properties of the storage tank and DHW distribution are assumed to be similar for all DHW systems, disregarding heating technology and fuel.

Mjønes et al. (2012) assume exhaust systems for pre-2001 buildings and balanced ventilation for all newer buildings, and this will also be the basis for the calculations. They define infiltration losses for all buildings within the time frame of this project at 1.5 air changes per hour at 50 Pa pressure difference. This means a TABULA air exchange rate of between 0.1 and 0.2, according to Loga and Diefenbach (2012a). In order to assure that the values are met, the infiltration loss is set to 0.1 per hour for these buildings. NS 3700 requires passive houses to have an air tightness of maximum 0.6 1/h at 50 Pa pressure difference. This gives a TABULA air exchange rate of 0.05 1/h.

Air exchange values are also given by Mjønes et al. (2012) for the original buildings. The air exchange from ventilation is calculated by subtracting the air exchange by infiltration from these values. For the upgraded building, the minimum air exchange rate from TEK 10 is used.

All rehabilitation projects will include changing to balanced ventilation in order to meet the air exchange demands set by the current standards.

Building envelope

The U-values in the TEK 10 and Passive renovation strategies are based on the values in Table 10, where the median of typical U-values for passive houses are chosen for the Passive rehabilitation. This will increase the probability for the building to fulfil the requirement of Eq. 3. The U-values of the TEK 10 renovation might be higher than necessary when following the requirements in Table 10, and this will be investigated when comparing the resulting energy use with the requirements in Eq. 2.

The retrofit insulation is assumed to be added to the outside wall, and therefore, the thermal bridging will be reduced for both refurbishment packages. Calculating thermal bridges is complicated, and is usually based on simplifications. Table A4 in NS 3031 defines typical thermal bridges for newer buildings, based on the insulation thickness and thermal bridge barriers in the wall. As no better source has been found, these numbers are assumed to be valid for the two oldest building typologies. The wall type with 20 cm thick mineral wool insulation and 5 cm thick thermal bridge barrier is the closest match to the typical wall in these buildings, which gives a thermal bridge value of 0.12 W/m2K. The thermal bridges are assumed to be reduced to the desired value in the standards.

U-values for doors and windows were chosen based on example windows and doors from Holte AS (2013), as the price for these were important in order to perform the LCC calculation afterwards. The building is assumed to have six doors. The doors are assumed to have the dimensions 0.9 m $\times$ 2 m, which is the minimum requirement in TEK 10.

By comparing U-values for the different times from (Mjønes et al., 2012) with the U-values for different technologies from Broli (2000), the buildings from 1981-2000 are assumed to have two-layered, sealed insulated windows with one metal coated glass, filled with air. The newest original buildings have an additional glass sheet and argon filling in one of the cavities. The standard rehabilitation is assumed to involve one ordinary and two metal coated glass sheets with argon filling in both cavities. The table does not provide a technology with as low U-values as required for passive houses, but according to Enova (n.d.-a), this can be achieved by using the same type of windows with better insulated frames.

The TABULA sheet (Institut Wohnen und Umwelt GmbH, 2013b) provides some values for energy transmittance through radiation for different window technologies for Norwegian buildings, and these are used as basis for the calculations. The radiation transmittance values are thus selected by assuming the technology distribution assumed above. The value was not defined for the windows chosen for extensive rehabilitation, and is therefore assumed to be the same as for the other rehabilitation window type. As they have the same structure, this is not unlikely.

Other data and assumptions

Vertical irradiation data from NS 3031 and temperature and other irradiation data from Enova (2004) are used as a basis for the calculations. As the data from Enova was given on a yearly basis, the values in the table had to be calculated in order to find the average values of the heating season. The beginning and end of the heating season was assumed based on the coldest months, in order to calculate the values in the table.

The indoor temperature is set to 22 °C for all buildings. The roof is assumed to be flat, and without windows. Spaces for attic, basement, and stairways are not included in the calculations. This assumption holds if these areas are unheated.

Input values chosen for testing

Energy balance calculations are conducted in order to find the yearly energy demand for DHW and room heating for different buildings and renovation scenarios.

Based on properties of stereotypical apartment blocks as defined by Mjønes et al. (2012) and the discussion in Chap. 3.2, the areas chosen for describing the stereotypical apartment blocks are gathered in Table 20.

Table 20: Overview of areas chosen for standard apartment blocks, used in the energy balance calculations.

	Construction year			
TABULA parameter name	**1981-1990**	**1991-2000**	**2001-2010**	**Unit**
$A_{C,ref}$	1824	1656	1704	m^2
$A_{window.north}$	109	99	102	m^2
$A_{window.south}$	164	149	153	m^2
$A_{env,wall}$	1030	668	665	m^2
$A_{env,window}$	274	248	256	m^2
$A_{env,floor}$	456	414	426	m^2
$A_{env,roof}$	456	414	426	m^2

The main renovation scenarios used for the energy calculations are as follows:

None
The building remains at their original state

Minimum
The building is subject to renovation related to wear and tear. This case takes into account that some building parts will not be available in as low standards as they were at the construction time of the building. Windows and doors are exchanged for units similar or slightly better, depending on windows found for cost calculations. The DHW tank and piping are replaced with modern units for buildings constructed between 1981-1990.

TEK 10
Energy rehabilitation fulfilling the requirements set by TEK 10

Passive
Energy rehabilitation based on typical values required for obtaining passive house standard, as defined in NS 3700.

Tables 21 - 23 contain the TABULA values designed for calculating the energy balances in this project. As seen in Table 23, a minimum rehabilitation has been omitted for the newest building cohort. This is because the U-values for windows and doors matches the example doors and windows used in the LCC calculations.

For all building types and rehabilitations, the internal heat gains, energy demand for DHW, recoverable heat from the DHW system, solar heat gains, total net energy demand for room heating, and total net energy demand for the heating source for room energy heating will be calculated and presented.

Table 21: Overview of TABULA values varying according to rehabilitation packages, used for energy balance calculations. Buildings constructed between 1981 and 1990.

TABULA parameter	Rehabilitation None	Minimum	TEK 10	Passive	Unit
$g_{gl,n}$	0.63	0.63	0.5	0.5	-
$n_{air,use}$	0.3	0.3	0.4	0.45	1/h
$n_{air,infiltr}$	0.1	0.1	0.1	0.05	1/h
$\eta_{ve,rec}$	0	0	0.8	0.8	-
$q_{s,w,h}$	2.4	1.9	1.9	1.9	kWh/m^2·year
$q_{d,w,h}$	3	0.8	0.8	0.8	kWh/m^2·year
$q_{s,w}$	3.6	2.9	2.9	2.9	kWh/m^2·year
$q_{d,w}$	4.6	1.4	1.4	1.4	kWh/m^2·year
$R_{0,wall}$	3.45	3.45	5.56	9.09	m^{2}K/W
$R_{0,window}$	0.45	0.63	0.83	1.43	m^{2}K/W
$R_{0,floor}$	5.00	5.00	6.67	12.50	m^{2}K/W
$R_{0,door}$	0.50	0.63	0.83	1.43	m^{2}K/W
$R_{0,roof}$	5.00	5.00	7.69	11.76	m^{2}K/W
ΔU_{thr}	0.12	0.12	0.06	0.03	W/m^{2}K

Table 22: Overview of TABULA values varying according to rehabilitation packages, used for energy balance calculations. Buildings constructed between 1991 and 2000

TABULA parameter	Rehabilitation None	Minimum	TEK 10	Passive	Unit
$g_{gl,n}$	0.63	0.63	0.5	0.5	-
$n_{air,use}$	0.3	0.3	0.4	0.45	1/h
$n_{air,infiltr}$	0.1	0.1	0.1	0.05	1/h
$\eta_{ve,rec}$	0	0	0.8	0.8	-
$q_{s,w,h}$	1.9	1.9	1.9	1.9	kWh/m^2·year
$q_{d,w,h}$	0.8	0.8	0.8	0.8	kWh/m^2·year
$q_{s,w}$	2.9	2.9	2.9	2.9	kWh/m^2·year
$q_{d,w}$	1.4	1.4	1.4	1.4	kWh/m^2·year
$R_{0,wall}$	3.45	3.45	5.56	9.09	m^{2}K/W
$R_{0,window}$	0.45	0.63	0.83	1.43	m^{2}K/W
$R_{0,floor}$	5.00	5.00	6.67	12.50	m^{2}K/W
$R_{0,door}$	0.50	0.63	0.83	1.43	m^{2}K/W
$R_{0,roof}$	5.00	5.00	7.69	11.76	m^{2}K/W
ΔU_{thr}	0.12	0.12	0.06	0.03	W/m^{2}K

Table 23: Overview of TABULA values varying according to rehabilitation packages, used for energy balance calculations. Buildings constructed between 1991 and 2000

TABULA parameter	Rehabilitation None	TEK 10	Passive	Unit
$g_{gl,n}$	0.5	0.5	0.5	-
$n_{air,use}$	0.4	0.4	0.45	1/h
$n_{air,infiltr}$	0.1	0.1	0.05	1/h
$\eta_{ve,rec}$	0.5	0.8	0.8	-
$q_{s,w,h}$	1.9	1.9	1.9	$kWh/m^2 \cdot year$
$q_{d,w,h}$	0.8	0.8	0.8	$kWh/m^2 \cdot year$
$q_{s,w}$	2.9	2.9	2.9	$kWh/m^2 \cdot year$
$q_{d,w}$	1.4	1.4	1.4	$kWh/m^2 \cdot year$
$R_{0,wall}$	3.70	5.56	9.09	m^2K/W
$R_{0,window}$	0.63	0.83	1.43	m^2K/W
$R_{0,floor}$	7.14	7.14	12.50	m^2K/W
$R_{0,door}$	0.63	0.83	1.43	m^2K/W
$R_{0,roof}$	7.14	7.69	11.76	m^2K/W
ΔU_{thr}	0.06	0.06	0.03	W/m^2K

Additionally, various parts of the rehabilitation packages will be investigated in order to examine their effects on the total energy demand. This includes:

New windows and doors (W/D)
This involves changing the values $g_{gl,n}$, $R_{0,window}$, and $R_{0,door}$ to the values defined in the TEK 10 and Passive rehabilitations.

Balanced ventilation system (Ventilation)
This involves changing the value $\eta_{ve,rec}$ to 0.8, which is the basis for both the TEK 10 and Passive rehabilitations. $n_{air,infiltr}$ is kept constant, as no infiltration-reducing measures are implemented, while $n_{air,use}$ is changed to 0.5 in order to satisfy the air quality requirement set by TEK 10 and NS 3700.

New DHW tank and distribution system (DHW)
$q_{s,w,h}$, $q_{d,w,h,}$, $q_{s,w}$, and $q_{d,w}$ are changed from the original values for the oldest building type, to the value of the minimum rehabilitation.

Replacing the building envelope only could also be an interesting aspect, but as this will generally lead to a decrease in air quality an possibly also rot, this option is not considered in the calculations.

Lastly, H_{tr} and H_{ve} will be found for all building alternatives mentioned above, in order to find the design heat load (P_{dim}) of the space heating necessary for maintaining a satisfactory indoor temperature. The method will be based on the simplified method in the standard NS-EN 12831, as described by Thue and Novakovic (2007), where the design heat load can be found by Eq. 5.[x]

[x]The equation is a combination of several equations in the chapter, and based on a reheat factor of 0, which is valid for buildings with constant heating. This is a simplification, as the temperature is likely to vary over time. For apartment buildings with a high thermal mass, the reheat factor can add 2 to 45 W/m^2 to the design heat load, depending on the temperature the room has sunk to, the period of energy sinking, and the desired period until normal indoor temperature is reached again (Thue and Novakovic, 2007). When taking the high uncertainties connected to reheat factor into consideration, as well as the fact that modern buildings with a lower thermal envelope has lower reheat factors, this assumption is believed to be reasonable.

$$P_{dim} = (H_{ve} + H_{tr}) \cdot (DT_i - DT_e) \tag{5}$$

Where:
H_{ve} and H_{tr} are defined by the TABULA method, and thus found by using the spreadsheet.
DT_e = -20 °C for Oslo, Blindern (Stene, 2001)
DT_i = 20 °C, from Eq. 6, described by Thue and Novakovic (2007).

$$DT_i \sim \vartheta_{int} - 2°C \tag{6}$$

The design heat load will be used further in the cost calculations.

3.3 Heating systems

Based on the information in Chap. 2.2.4, these air heating systems are assumed to be typical for the different construction years, and will be used as a basis for all calculations. In order to simplify later calculations, these heating systems are assumed to cover all buildings, and their share is given in parentheses:

1: 1981-1990

1E: Electric radiators (87 %)

1O: Electric radiators and oil boiler (13 %)

2: 1991-2000

2E: Electric radiators (100 %)

3: 2001-2020

3E: Electric radiators (86 %)

3P: Electric radiators and pellets boiler (7 %)

3D: District heating (7 %)

As fuel oil boilers are soon to be prohibited, option O is not a valid rehabilitations alternative. The E alternatives do not fulfil TEK 10 or NS 3700, and are therefore not always an option either. Based on the information in Chap. 2.2.4, these are assumed to be the most relevant rehabilitation alternatives for air heating sources:

D: District heating

P: Electric radiators and pellets boiler

Hg: Geothermal heat pump

From the costs gathered in App. B.2, air-air heat pumps seem to have low energy and installation costs, and will therefore also be considered an alternative. In order to allow the heated air to flow to all rooms, one heat pump is installed in every apartment. This alternative will be referred to as Ha. Additionally, the effects of adding solar heaters for heating of DHW is calculated, and this will be referred to as alternative s.

After calculation of energy use, the most interesting alternatives will be picked for further calculations in a discussion. The rehabilitation alternatives will be based on the renovation strategies defined for the energy balance model, combined with the energy system alternatives defined above, and possibly also with a solar collector for DHW heating. Buildings from all construction years will be examined, but the building type with the largest potential for energy saving will be tested with a larger amount of renovation strategies. This should be done to all buildings, ideally, but this is done in order to limit the scope of the project, as the possible combinations are numerous. The heating system efficiencies will be the same as those in Table 11.

3.4 Cost model

The cost model is based on the LCC principle and the scenarios chosen for the energy balance model. The standardised approach for calculating life cycle costing (LCC) analyses in buildings is defined in NS 3454 (Standard Norge, 2013), and ISO 15686-5 (the International Organization for Standardization, 2008) provides a standard for LCC calculations in general. All information on LCC in this project is collected from these two sources.

An LCC analysis takes into account all relevant costs arising from acquisition through operation to disposal of an asset. For buildings, an asset can refer to an entire building or structure, a system, component or part. LCC is useful for determining whether a project meets the financial standards set by a customer, or when comparing alternative projects.

LCC is usually based on net present value (NPV), which is defined as the sum of all future discounted cash flows. NPV is calculated from Eq. 7:

$$NPV = \sum_{t=0}^{T} C_t \cdot d_t \tag{7}$$

where
t = start year of analysis period
T = end year of analysis period
C_t = costs in the certain year
d_t = discount factor, calculated from Eq. 8:

$$d_t = \frac{1}{(1+r)^T} \tag{8}$$

where
r = discount rate
T = length of analysis period

For a typical calculation, a preliminary building LCC analysis is conducted in the beginning with benchmark figures, and repeated later in the process when more accurate values have been found. When using LCC as a measure of comparison, important steps include defining the requirements for the assets, setting time period of analysis, and defining client priorities. Effort should be taken in order to assure that the scope is defined in such a way that all costs that vary between the options are included. When evaluating refurbishment cases, doing nothing should always be evaluated as an alternative. This will typically serve s a good base case when comparing the various options.

End-of-life residual values may be included when applicable, as well as taxes and price increase over time.

In this project, the main scenarios to be used for calculations will be chosen after a discussion on the various energy demands, found after the energy balance calculations. The objective is to establish the NPV of various rehabilitation alternatives, and compare these to the base cases, which are the NPVs connected with keeping the buildings in their original state. The costs evaluations will be based on the occupants' point of view, and include costs for acquisition (of materials or energy), installation, and maintenance. Costs of disposal and transportation are difficult to attain, and are thus omitted, as they are not assumed to be high compared to the other categories.

The time horizon was established in collaboration with the supervisor to last from the present year to 2050. This time frame should be long enough for calculating the long-term gains for rehabilitation measures with high investment costs and low energy prices. 36 years[xi]is possibly a longer time period than the staying time for an average inhabitant, but a low long-term NPV could still reflect positively on the inhabitants if it leads to lower rent or energy costs. Lifetimes chosen for calculations are economic lifetimes, which is in line with the LCC standards. The components could possibly last longer, but would likely represent higher costs because of wear and tear or obsolete technology.

Resale values are added for items in 2050. The calculation of these are based on an assumption that the resale value decreases linearly from the investment costs in the installation year to 0 at the end of the lifetime, in accordance with the example in NS 3454. Resale value, as well as financial support from Enova will be subtracted from the costs in the years applicable.

The discount rate is chosen as 5 %, matching that from the LCC on Swedish multi-family houses by Brown et al. (2013).

System boundaries are set to include acquisition costs of materials related to energy rehabilitation of the building envelope (new windows, doors, and insulation, as well as the wall claddings that need to be replaced when adding insulations in the walls), acquisition costs for energy delivered to the building for heating purposes, as well as acquisition and maintenance costs of the energy system for air heating and ventilation. Maintenance costs are assumed to be similar for all building envelopes, disregarding rehabilitations, and the same is assumed for maintenance and acquisition of DHW system. These costs are therefore not included in the cost analysis.

The NPV of acquisition costs (including ventilation), energy costs, and maintenance within the scope, minus the benefits from Enova support or resale value will be calculated based on Eq. 7. This will be done in an electronic Excel worksheet, provided in App. D. The lowest resulting NPV will reflect the most beneficial rehabilitation project. Every possible combinations of heating sources, energy balances, and construction years will not be tested, as this is regarded as too time consuming. As the goal is to establish the most cost-efficient, realistic rehabilitation alternative, alternatives expected to yield a higher NPV than other alternatives with the same energy balance are omitted. A short comment on priorities will be added among the results.

The cost calculations of the buildings will be based on an upgrade of the energy system in the year 2014, then changing the various parts of these systems after their individual lifetime until he year 2050. This involves that the energy demand will stay unchanged for all years after the

[xi]Comparatively, Brown et al. (2013) based their LCC on Swedish multi-family buildings on a time period of 50 years.

rehabilitation is done. For the base cases, minimum upgrades only will be carried through. For the oldest building cohort, the base case calculations will be based on renovation of all building components in the year 2014 (as they are close to the end of their lifetime anyway at that point), except for the hydronic heating system and cladding, which will be upgraded in 2025 [xii]. The same assumptions are used for the 1991-2000 buildings, except that a renovation of hydronic system and cladding will happen in 2035. For the newest building type (2001 and later), the original building parts are renovated based on the construction year being 2005. The energy renovations are assumed to be carried out in 2014. This is unrealistic, as the heating system and building are both far from the end of their lifetimes, but allows to assess the consequences over a longer time horizon.

In order to limit the scope of the project, most prices are based on only one source or supplier. The prices have been defined as to include the same cost parameters (installation, maintenance, demolition, labour, etcetera), but this is certainly a source for errors, as the information in some cases has been scarce. Additionally, different sources could choose to define these parameters differently. In order to keep the costs as comparable as possible, it is considered an advantage to use the same source for as many rehabilitation components as possible. However, the accuracy of the values is also of great importance, and a source based on information from several suppliers is preferable. Based on these criteria, Holte Kalkulasjonsnøkkelen (Kveim, 2013) and Norsk Prisbok (Jensen, 2013) were chosen as the preferred sources, and always used as a basis when containing the necessary information. In some cases, these sources include a multiplication factor based on building area for the prices, which reflect the likely bulk purchase discount.

The thickness of the necessary retrofit insulation has been calculated to an accuracy of 1 cm. The insulation used in the LCC example is in reality not delivered in such specific thicknesses. However, as the price of insulation varied to a high degree depending on the different cases (as opposed to for instance many of the heating technologies, where a large increase of maximum power only results in a small price increase) and was approximately linearly dependent of the insulation thickness, this was considered as a just simplification. It is possible that other suppliers could deliver a greater variety of insulation thicknesses, which would make this a realistic simplification. In order to decide the prices, the price of the medium alternative for Rockwool B-plate was divided by its thickness, in order to find the costs per cm. The "B-plate" rock wool used for calculations is normally delivered in the thicknesses 98 mm (33.10 NOK/m^2), 148 mm (49.20 NOK/m^2), and 198 mm (65.60 NOK/m^2). (The rock wool is delivered in standardized pallets, and it is therefore likely that there will be some rock wool left over, causing the price to be a little higher in reality.) When retrofitting insulation, the layers would therefore be one or a combination of these thicknesses. However, in order to simplify the calculations, it is assumed that the insulation can be delivered in the exact thickness required to reach the defined U-values for TEK 10 or passive house. The prices are approximately linear according to the thickness. In the LCC, the prices will be based on the insulation thickness of 98 mm, which means that the costs are 0.3378 NOK/m^2 for every mm thickness of the insulation material.

Opposed to the LCC standards, cost developments over time has not been evaluated in the project. This choice was made based on the high uncertainties of such developments. A sensitivity analysis has been included for all scenarios, where the costs of electricity are doubled. This will give an indication as to which energy sources might be the better choice in the future, if electricity price continue to rise as in Fig. 10, or other alternative become cheaper as the technologies mature or their market share increases.

[xii]The oil heater LCC base case will be a theoretical calculation, as installation of new oil heaters are prohibited.

Additional simplifications and input values can be found in Apps. B.1 and B.2, respectively. A calculation example is provided in App. B.3.

3.5 Scenario model

The model developed as part of the work by Sandberg et al. (2014) and the recommendations from their work are used for establishing the number of existing buildings, and to predict the renovation and demolition development until 2050. The input values used in this project that differ from the standard values in the model are gathered in Fig. 19. The model requires the building stock to be separated into five cohorts spanning the time period 1800-2100, and so values in columns O and P are chosen to show results for the building cohorts investigated in this project: 1981-1990, 1991-2000, and 2001-2010. Cohort no. 1 and 5 will be ignored. Probability functions are chosen in column K and L, setting Weibull for demolition and normal for renovation, as recommended by the developers for the most realistic result. When normal distribution is applied to renovation, column H denotes the mean, I the standard variation, while J is not used. In agreement with the advisor, the mean is set to 40 years, which reflects a deep renovation of façades. The default standard deviation is set to 10 in the figure, but some simulations will be done with a lower standard deviations as well, in order to investigate its effects.

H	I	J	K	L	M	N	O	P
par1_renov	par2_renov	par3_renov	probability function demolition	probability function renovation	Number of cohorts	Cohort number	Start year	End year
40.00	10.00	10.00	2	1	5	1	1800	1980
40.00	10.00	10.00				2	1981	1990
40.00	10.00	10.00	Probability function specifications:			3	1991	2000
40.00	10.00	10.00	1 if normal, 2 if Weibull.			4	2001	2010
40.00	10.00	10.00				5	2011	2100

Figure 19: Input values chosen for this project in the building stock scenario model by Sandberg et al. (2014).

From the model by Sandberg et al. (2014), outputs for the amount of original, renovated, and demolished compact houses every year will be used for predicting the future energy demand and emissions from the Norwegian building stock. The current heating systems in the building stock are assumed to match those from Chap. 3.3, and scenarios for the total energy use for the building stocks will be calculated by Eq. 9 for the years 2014-2050.

$$E_{tot} = \sum_{i=1}^{3} A_i \cdot [N_{o,i} \cdot \sum_{j=1}^{n}(E_{o,j} \cdot p_j) + N_{r,i} \cdot \sum_{j=1}^{n}(E_{r,j} \cdot p_j)] \tag{9}$$

where

E_{tot}	=	total energy use for heating in the building stock over one year [kWh]
i	=	cohort number
A_i	=	average area of apartments, cohort i [m^2]
$N_{o,i}$	=	number of existing apartments in original standard, cohort i
j	=	heating system
n	=	number of heating systems
$E_{o,j}$	=	energy use in buildings for heating system j in original standard [kWh/m^2]
p_j	=	share of buildings in cohort with heating system j [%]
$N_{r,i}$	=	number of existing rehabilitated apartments, cohort i
$E_{r,i}$	=	energy use in buildings for heating system j, renovated [kWh/m^2]

It is assumed that a house can undergo one rehabilitation only over the time horizon, and that only buildings in original standard are demolished, which means that the amount of demolished buildings are subtracted from the existing original buildings in order to find $N_{o,i}$. Rehabilitations are assumed to only happen after 2014. The energy use for heating includes energy delivered to building for air-heating and DHW, while energy demand for appliances is excluded.

Rehabilitation strategies for each heating system to be used as a basis for calculations, will be chosen after a discussion of the results from the energy balance and cost model. The strategies will include minimum rehabilitation, most profitable, lowest emissions, and building standards (TEK 10 and Passive). These will be compared to a scenario with constant energy consumption per household (i.e. no renovations) and a scenario where all renovated buildings use zero energy for heating purposes (ZEB). Neither of these scenarios are realistic, but will be useful for comparing the effects of the energy rehabilitations compared to the potential energy savings.

The emissions will be calculated similarly to the energy consumption, by Eq. 10, with the same energy scenarios and rehabilitation strategies.

$$e_{tot} = \sum_{i=1}^{3} A_i \cdot [N_{o,i} \cdot \sum_{j=1}^{n}(E_{o,j} \cdot p_j \cdot e_{o,j}) + N_{r,i} \cdot \sum_{j=1}^{n}(E_{r,j} \cdot p_j \cdot e_{r,j})] \tag{10}$$

where

e_{tot}	=	total CO_2 emissions for heating in the building stock over one year [g]
$e_{o,j}$	=	CO_2 emissions for heating system j in original standard [g/kWh]
$e_{r,j}$	=	CO_2 emissions for heating system j, renovated [g/kWh]

$e_{o,j}$ and $e_{r,j}$ will be based on the values from Table 12. For some of the scenarios, values from Table 19 will be used as a basis in order to examine the effects of possible changes to emissions from energy production. The emissions are assumed to change linearly between those values provided in the table.

4 Results and discussion

4.1 Energy balance

4.1.1 Results

This chapter contains all results from the energy balance model, calculated as described in Chap. 3.2. The results are sorted by the construction year of the apartment blocks, as areas and heating technologies of these cohorts vary.

Yearly energy from internal heating sources are gathered in Table 24. This is energy produced from inhabitants, electrical equipment, etc. In the TABULA method, this energy is subtracted from the total energy demand, making it "free" energy.

Table 24: Internal heat gains for stereotypical apartment blocks, sorted by building construction year.

Construction year	Specific energy [kWh/m^2·year]	Energy [MWh/year]
1981-1990	27.30	49.80
1991-2000	27.22	45.08
2001-2010	27.47	46.81

Yearly DHW demands are collected in Table 25, based on a yearly net demand of 30 kWh/m^2. Net energy demand is the energy required for DHW heating by the inhabitants, but when considering the losses from the DHW tank and distribution system, the total energy demand is higher, as presented in the right column.

Table 25: Yearly energy demand for DHW

Construction year	Net DHW demand [MWh]	Energy delivered to DHW heater [MWh]
1981-1990, original standard	54.72	69.68
1981-1990, rehabilitated	54.72	62.56
1991-2000	49.68	56.80
2001-2010	51.12	58.45

Although heat is lost from the DHW system, some of it will be conducted through building parts and contribute to room heating, reducing the energy demand from air heating sources further. Table 26 contains the values of these heat contributions.

Table 26: Yearly recoverable heat from DHW system, contributing to room heating

Construction year	Total heat [MWh]	Specific heat [kWh/m^2]
1981-1990, original standard	9.01	4.94
1981-1990, rehabilitated	4.49	2.46
1991-2000	4.08	2.46
2001-2010	4.23	2.48

Tables 27 - 29 contain energy balance results from buildings constructed 1981-1990, 1991-2000, and 2001-2010, respectively. The energy related to non-rehabilitated buildings are stated in the first line, followed by the various rehabilitation alternatives. The first column contains the total heating demand for the building, which is the heat required for eliminating the heat losses from the building, while maintaining the desired indoor temperature. The necessary heat output from the heating source, matching the heat losses, can be found in the second column. The energy required for space heating will vary according to the efficiencies of the heating system. This is lower than the total space heating demand, as a large part of the energy demand is covered by internal heating sources, heat leaks from DHW, heat recovered by heating coil, or solar heat gains, which are provided in the right column.

Table 27: Solar heat gains and net yearly energy demands for space heating for stereotypical apartment blocks constructed between 1981 and 1990, sorted by renovation packages and parts of renovation packages. W/D = windows and doors.

	Net yearly energy demand or flow [kWh/m^2]		
Rehabilitation	Total space heating	From space heating source	Solar heat gains
Original condition	108.69	63.66	12.79
Minimum rehab.	99.56	57.12	12.75
TEK 10	86.24	14.17	10.19
Passive	68.68	-2.59	10.05
W/D Minimum	99.56	54.66	12.75
W/D TEK 10	93.34	50.68	10.21
W/D Passive	85.52	43.01	10.18
Ventilation	117.32	40.56	12.82
DHW system	108.69	66.13	12.79

Table 28: Solar heat gains and net yearly energy demands for space heating for stereotypical apartment blocks constructed between 1991 and 2000, sorted by renovation packages and parts of renovation packages. W/D = windows and doors.

	Net yearly energy demand/flow [kWh/m^2]		
Rehabilitation	Total space heating	From space heating source	Solar heat gains
Original condition	99.42	56.99	12.75
Minimum rehab.	93.17	50.84	12.72
TEK 10	82.47	10.51	10.17
Passive	66.46	-4.63	10.02
W/D Minimum	93.17	50.84	12.72
W/D TEK 10	86.88	46.82	10.19
W/D Passive	78.98	39.11	10.14
Ventilation	108.08	33.85	12.79

Table 29: Solar heat gains and net yearly energy demands for space heating for stereotypical apartment blocks constructed between 2001 and 2010, sorted by renovation packages and parts of renovation packages. W/D = windows and doors.

	Net yearly energy demand/flow [kWh/m^2]		
Rehabilitation	Total space heating	From space heating source	Solar heat gains
Original condition	92.05	31.87	10.21
TEK 10	81.99	10.05	10.16
Passive	66.25	-4.82	10.02
W/D TEK 10	85.75	25.69	10.18
W/D Passive	77.83	18.01	10.13
Ventilation	92.05	19.86	10.21

The calculated design heat loads of the varius building and renovation strategies are gathered in Table 30. These values determine the necessary maximum power required from the heatings source.

Table 30: Design heat load for all rehabilitation alternatives

	P_{dim} [kW], sorted by contruction year		
Rehabilitation	1981-1990	1991-2000	2001-2010
Original condition	808	724	61.29
TEK 10	636	724	54.41
Passive	369	724	43.73
W/D TEK 10	700	724	56.97
W/D Passive	565	724	51.57
Ventilation	808	724	61.29

4.1.2 Discussion

Main findings and comparison to literature

For the simulated values in Tables 27 - 29, the oldest buildings have largest potential for energy reduction, although the total energy demand is fairly similar for buildings from all construction periods. This is not in accordance to the values in Table 2, where the energy use is shown to have increased for newer buildings. Comparing the values for energy demand for air heating further, it is apparent that the values from the simulations produce an energy demand for space heating that is about 33 % higher, 14 % higher, and 41 % lower than that for the actual original buildings from oldest to newest production year respectively. It is likely to assume that the calculated values should be lower, as losses in the energy system are not taken into account. The results for original buildings are, however, between those from Hille et al. (2011) and Pauliuk et al. (2013) for buildings constructed between 1981 and 1990. Fig. 7 shows a different energy development than Table 2. Here, the energy demand has decreased steadily for the typical buildings, and the total energy consumption is around 50 % higher than the values in the table. The graph does not distinguish between energy purposes, but one could certainly assume that this means a higher demand for room heating energy as well. In any case, the differences between these values support the notion that comparing the results from this exercise to realistic data is difficult. Both sources state that the values are based on official statistics, but these might be different. The differences also probably arise from different definitions of buildings and stereotypical apartments. Based on the simulation results, the building type constructed between 1981 and 1990 shows the highest energy saving potential, and is therefore chosen as the main stereotypical building for further calculations.

Delivered energy for DHW is around twice as high for he calculated values (Table 25) than for the values in Table 2. Following the literature, the energy demand for heating should be around 30 % of the total energy demand, while delivered energy for room heating should make up for around 45 %, which means that the DHW demand should be 2/3 of the energy demand for the room heater. This is not supported by the results, where even the oldest original buildings have a lower energy demand for room heating than for DHW.

When comparing the total space heating in Tables 27 - 29 (with an additional heat demand of 28.9 kWh/m^2, in accordance to NS 3031) with the values in Table 9, it is clear that both real and simulated original buildings constructed between 1981 and 1990 qualify for the energy grade D. A simulated TEK 10 renovation, and even the D/W TEK 10 renovation produces an energy grade of C, which means that the TEK 10 demands are satisfied in both cases (unless the energy carrier efficiency is very low.) Real buildings from 1991-2010 also qualify for a D energy grade, but the simulations produce a C, which means that the buildings already should fulfil the TEK 10 standard. When carrying through the TEK 10 renovations as defined in this project, the energy grade is increased to a B. For W/D TEK 10, the grade remains at C.

The Passive rehabilitation results in a negative energy demand from space heating sources, which means that overheating will occur. The TABULA calculation method does not include energy for cooling purposes, and this becomes a significant problem when buildings become sufficiently tight. As the calculation model is not dynamic, the positive energy demand in the other buildings does not guarantee that the buildings have no need for cooling in the hottest days, but it is reasonable to believe that it is not substantial. All in all, it seems like the TABULA calculations method is better suited for upgrading buildings of a poorer standard, and with less ambitious renovation strategies.

Upgrading the ventilation system results in a lower energy demand, and this could be a valid rehabilitation strategy. However, in order to limit the number of calculations in this project, the ventilation case will not be evaluated further in the next studies. Instead, ventilation heat will be included as a part of other packages. The improved DHW system for 1981-1990 buildings result in higher energy demand from space heating, as the losses from the DHW tank and system are decreased, leading to less heat leaks to the inside air. The energy demand for heating DHW will be additionally lowered, as seen in Table 26, resulting in a lower total energy demand for heating. As the Passive renovations produce extremely low results, these are considered to be too unrealistic for cost calculations. The alternative where only windows and doors are replaced results in energy demands lower than the TEK 10 renovation and can therefore be interesting as an alternative way of fulfilling the TEK 10 standard.

It is interesting to note that the energy demand following the building component limit in TEK 10 result in an energy demand so much lower than the TEK 10 maximum energy limit. This means that the TEK 10 standard can be easily met with minor changes. It is, however, possible that the official TEK 10 calculations could produce a different result. It also makes sense to keep the component standard much stricter than the energy standard, in order to make sure that the energy target is reached.

The resulting energy demand is much lower than for the buildings tested by Thyholt et al. (2009) (as described in Ch. 2.4.3), both for original and rehabilitated buildings. The Moderate and Ambitious renovation strategies are similar to the TEK 10 and Passive renovation, respectively, for the building envelope rehabilitations. The infiltration level is lowered to 3.0 1/h for the Moderate renovation, and further to 1.5 1/h in the Ambitious, which is similar to that of the original buildings tested in the project. The original building condition used as a basis for Thyholt et al. (2009) must therefore be based on a much higher infiltration loss. This is probably one of the reasons for the great difference in energy demand for the original buildings (140 vs. around 60 kWh/m^2). The standard building or the Moderate rehabilitation by Mjønes et al. (2012) do not include heat recovery systems, which also contributes to a higher energy demand. However, the parameters for the Ambitious renovation matches the parameters for the Passive, and these are still vastly different (140 vs. negative). It must therefore be concluded that this calculation method and/or the building definitions must be very different for these two studies.

Pauliuk et al. (2013) produced results more similar those in this project (Chap. 2.4.3). The building qualities of a standard building as defined in Table 14 are generally poorer than those chosen for the standard original buildings used for this project. However, Pauliuk et al. (2013)

calculated energy use for buildings as early as before 1950, and it is therefore safe to assume that the values should represent lower quality if the standard building is based on some average. The Package I and II renovations are similar to the TEK 10 and Passive renovations, respectively, for U-values of windows and thermal bridges. Package II is all in all very similar to the Passive rehabilitation, while the TEK 10 renovation consists of thinner layers of retrofit insulation, and higher standards for air tightness and ventilation heat recovery than Package I. These definition differences are part of the reason for the different results in energy use between the TEK 10 upgrade as defined in this project and Package I. On the other hand, the Passive and Package II renovation should be identical, but this is not the case. The results from the Package II renovation are probably the most realistic, as a passive house is not supposed to have an abundance of heat. Reasons for the different results could include different scope, variation between the models in parameters other than those already mentioned, calculation errors, or that the TABULA method is not well suited for low-energy buildings.

Evaluation of methodology

One of the main weaknesses of the energy balance calculations conducted for this project are the uncertainties connected to the values chosen for the properties of the stereotypical buildings. The sources did not agree on important factors such as energy demand and carriers, and the main source (Mjønes et al., 2012) pointed out that their values were largely based on assumptions and simplifications. In addition to gathering more specific information, further work on the model should include redefining some of the renovation packages, and possibly add new ones. The Passive renovation package was based on the average values needed for achieving the maximum Passive house energy demands set by NS 3700, but as the original buildings already had such a low energy demand, the average values might have been too high. A renovation package based on the maximum U-values (instead of those in parentheses) for NS 3700 in Table 10 might serve as a better low energy alternative if the results fulfil the limits set by Eq. 4.

The great differences between energy demand for DHW in literature and these results imply that the standard values are too high. The percentage from statistics are possibly not viable for building with low energy demand. The ratio between energy for room heating and DHW from the literature is also very different from the results, and this could also be an implication of the energy use being too low. It is, however, natural that the ratio will decrease for low energy buildings, as the DHW demand to a large degree is subject to occupant behaviour and not rehabilitations.

The energy consumption in the original buildings fits within the span of results from other sources, but it must be emphasised that these results vary significantly. The renovations yield energy demands that seem too low, and the renovation packages are possibly set to a standard that is unnecessary high for achieving TEK 10 and passive standard. This is a result of basing the TEK 10 renovation on the element requirements and the average values for achieving passive house standard for the Passive renovation.

The TABULA method itself could also be a source for errors, as it is not dynamic and does not take overheating into account. For buildings with a particularly low energy demand, solar shading or cooling is often necessary in order to avoid overheating on the warmest days of the year. These factors are not included in the TABULA model. When overheating occurs, the energy abundance is subtracted from the energy demand, which make the buildings look better than they actually are.

Other sources for error include simplifications and assumptions related to the building and that efficiency losses for heating systems are not included (the efficiency is, however, high for electricity, and will not affect the results greatly). All calculations are based on one climatic zone, and the results cannot be assumed to hold for other parts of the country.[xiii]The buildings used as basis are defined as standard buildings, which are not necessarily the same as average buildings.

Benefits of the model include the simplicity of changing values and producing results, as it is static and includes many standardised values if on is unsure about certain components. Energy flows are to a large degree separated, and easy to identify. As it is based on the TABULA model, the values can be used to compare results to other countries, as similar calculations have been conducted in several other European countries.

Implications and future work

Further work should include calculations with redefined rehabilitation packages. Even the most simple rehabilitation package, where only windows and doors were replaced with components with TEK 10 standard, reduced the energy demand to level C, thus fulfilling the TEK 10 energy requirement. The Passive rehabilitation package should be tested with the minimum passive house requirements, and these should be kept if this results in a satisfactory low energy demand as to satisfy the requirements in NS 3700.

More information should be gathered in order to improve the input parameters and control the accuracy of the final energy demand. This task requires more statistical data on existing buildings, both original and rehabilitated, especially for DHW energy demand, internal heating sources, and building components. The calculations have been done without regards to occupant behaviour, which could influence the final results in unexpected ways. More information should be gathered on this area as well.

The results include energy from direct energy use only, and a discussion on life-cycle energy demands, and how these compare to the direct energy use could certainly be interesting. As mentioned in Chap. 2.2.2, this could affect the results significantly.

The accuracy of the model would be improved by adapting it for dynamic analyses, but this would probably affect one of the main benefits of the model: its simplicity. If improving the accuracy is the main goal, the model should also include cooling demands and shading effects.

A sensitivity analysis should be carried out in order to find the most energy-efficient renovation measures, for instance whether retrofit insulation should be added on roof or walls, or whether it is best to upgrade the ventilation system or add retrofit insulation. The Kyoto pyramid (Fig. 9 could still provide a guideline for priorities as long as a sensitivity analysis is not conducted.

[xiii]The great variances between climate zones were confirmed in a pre-study for this project, where energy demand in original buildings were shown to be twice as high for other climate zones.

4.2 Costs

4.2.1 Results

Based on the previous discussion, buildings with Passive rehabilitations were assumed to have zero (not negative) energy demand from the heating source, as the results were considered unrealistic. The costs of installing a heating source will still be included for these renovation measures. Costs have not been calculated for the ventilation alternative, and improvements of the ventilation system will be evaluated as an integrated part of other rehabilitation packages.

Figs. 20 - 25 show total rehabilitation costs for the various building and rehabilitations alternatives. The color of the graphs refer to the rehabilitations packages (corresponding to the energy balance calculations) that determine the energy demand for heating. The various buildings and energy systems are identified with names such as 1ED, where the number represents the building age, the first letter the original heating system, and the last letter the heating system after renovation, if this is changed. The abbreviations are defined in Ch. 3.3.

The cost analysis is based on a limited share of costs for operating and running an apartment block, where all costs assumed to be constant for all buildings are omitted. The resulting NPV is therefore not representable for the total costs. Consequently, The results give indications as to which alternative is the most or least costly, but nothing on how the total costs would compare percentagewise.

Fig. 20 contains the results from the cost study on buildings constructed between 1981 and 1990. The results are presented in tables in App. B.4. The scenarios 1EP, 1Hg, and 1Es were not calculated further, after a quick overview of the cost details revealed that reducing the energy demand would not lead to lower costs than for the alternatives. Neither was the 1O alternative, as it is not allowed, and the 1OHg and 1OHa alternatives, as it could be seen from 1EHa and 1EHg that reducing the energy demand would not save money.

Fig. 21 contains results from similar buildings as Fig. 20, but with electricity costs at twice the level. Calculations on the same cases were omitted for the same reasons as described earlier.

Figs. 22 and 23 show results for buildings constructed between 1991 and 2000, for regular and doubled energy prices, respectively. Omitted calculations were chosen on the same basis as for 1EP, 1EHg, and 1Es.

Figs. 24 and 25 show results for buildings constructed between 2001 and 2010, for regular and doubled energy prices, respectively. Omitted calculations were determined similarly as for the buildings constructed between 1991 and 2000.

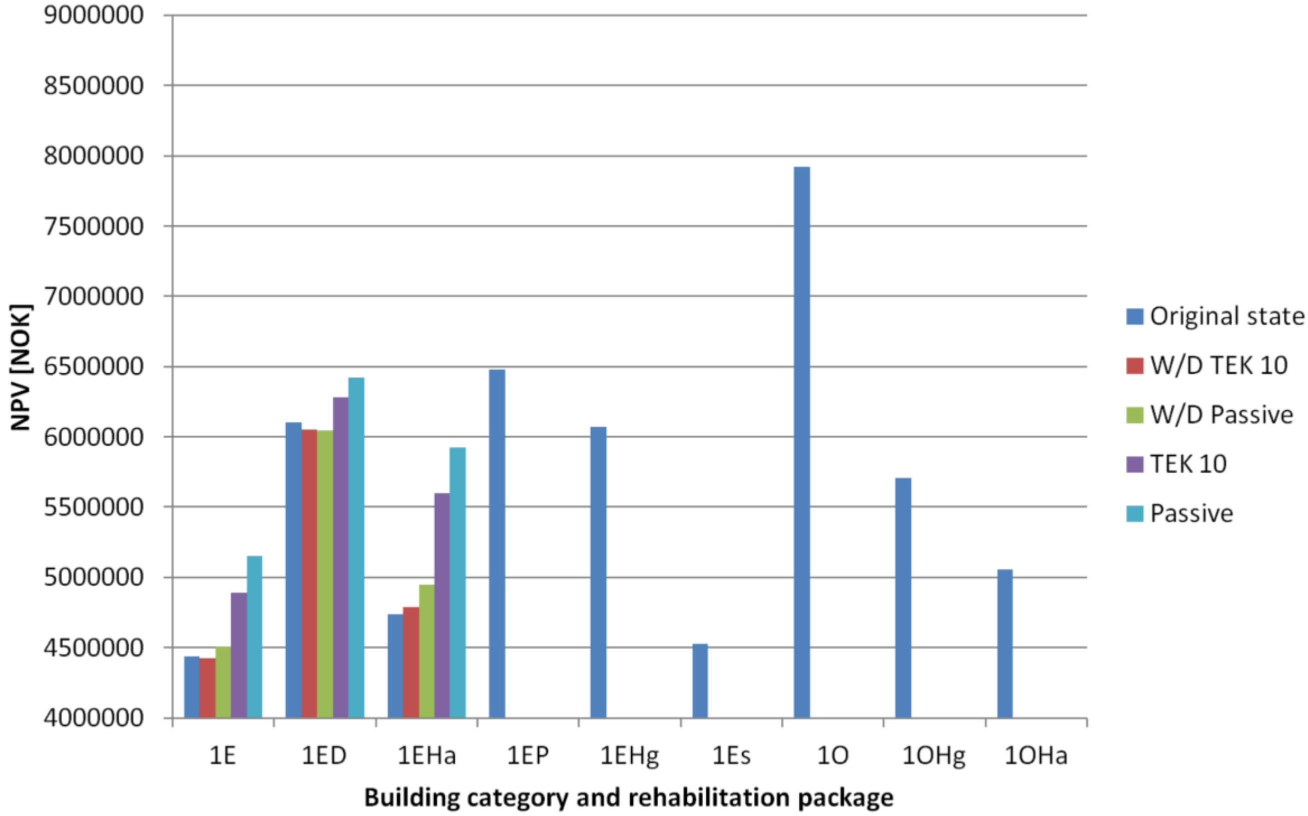

Figure 20: Resulting NPV after cost analysis of buildings constructed between 1981 and 1990 with present costs, sorted by original energy source and rehabilitation packages.

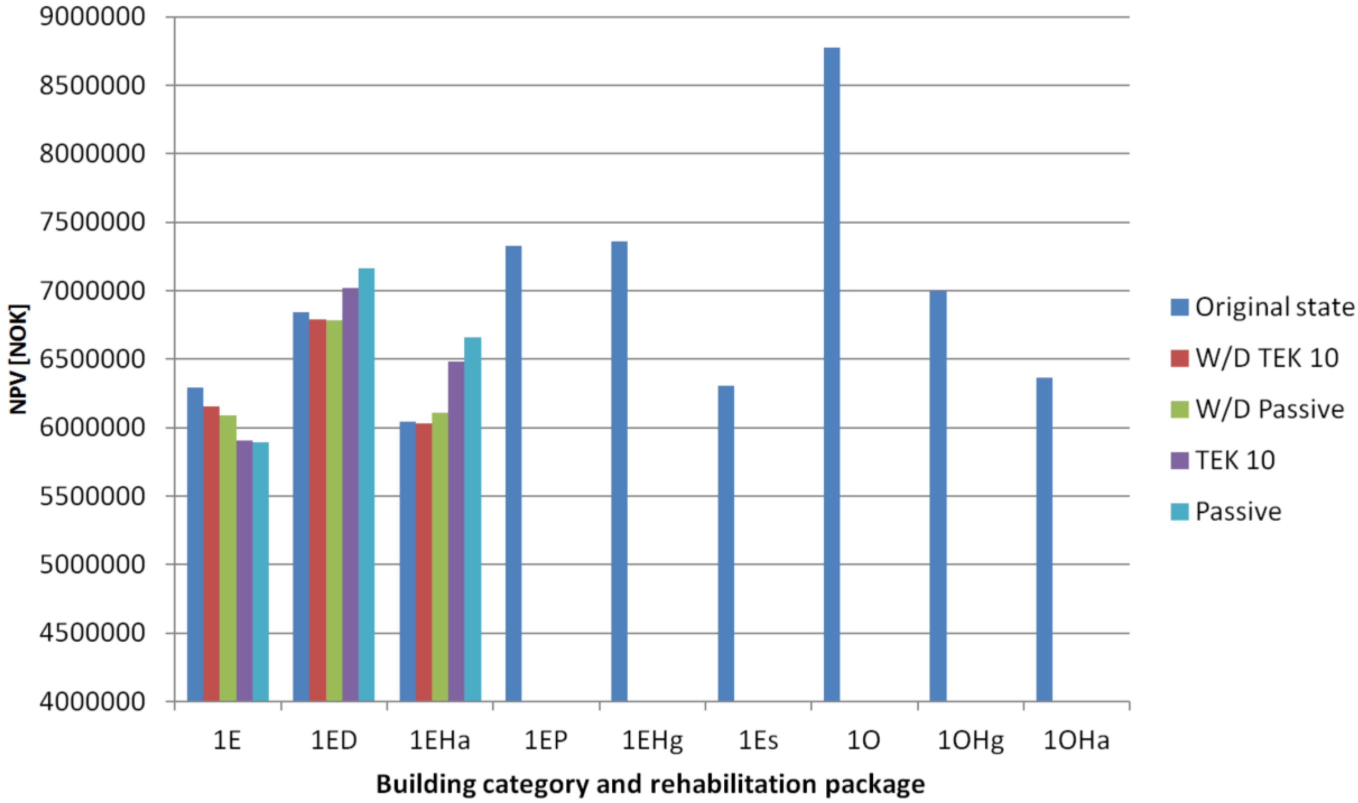

Figure 21: Resulting NPV after cost sensitivity analysis of buildings constructed between 1981 and 1990, assuming a doubling of the energy price for electricity, sorted by original energy source and rehabilitation packages.

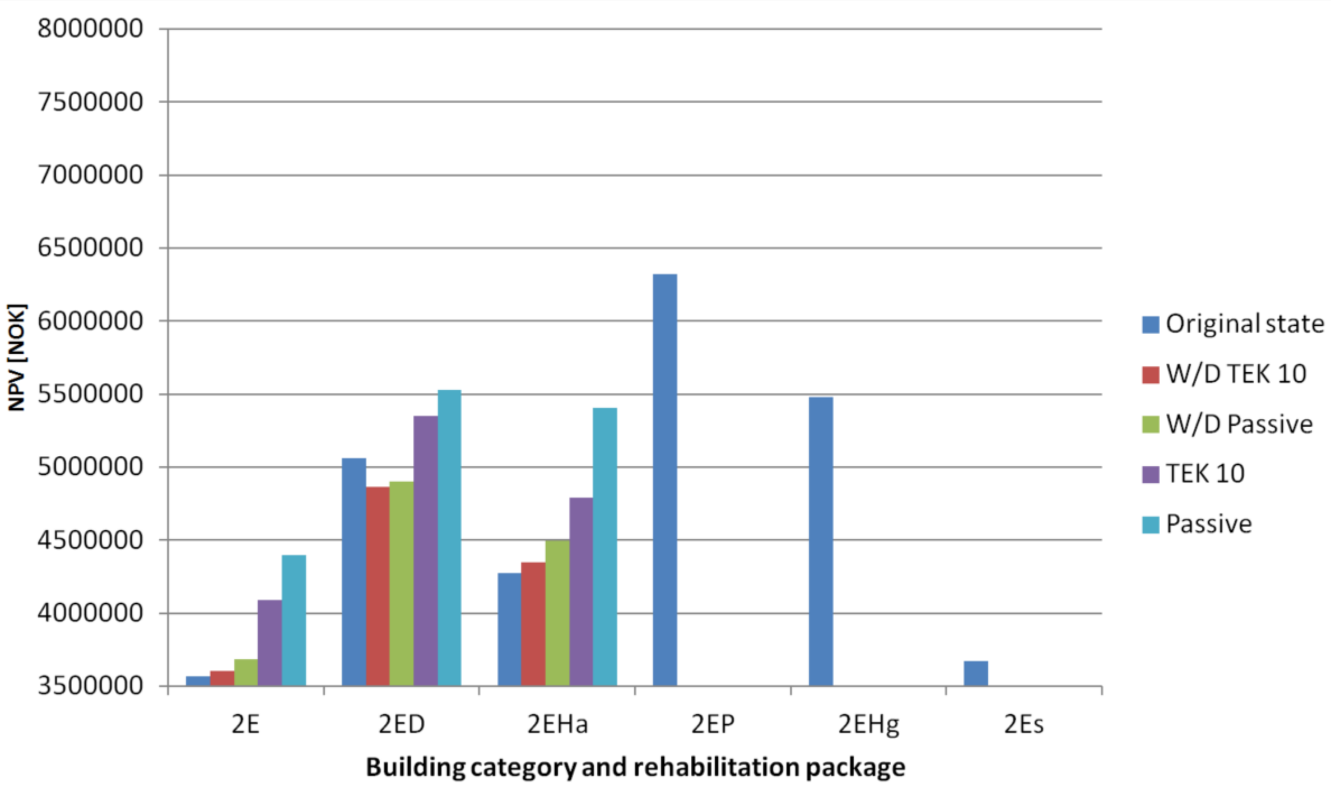

Figure 22: Resulting NPV after cost analysis of buildings constructed between 1991 and 2000 with present costs, sorted by original energy source and rehabilitation packages.

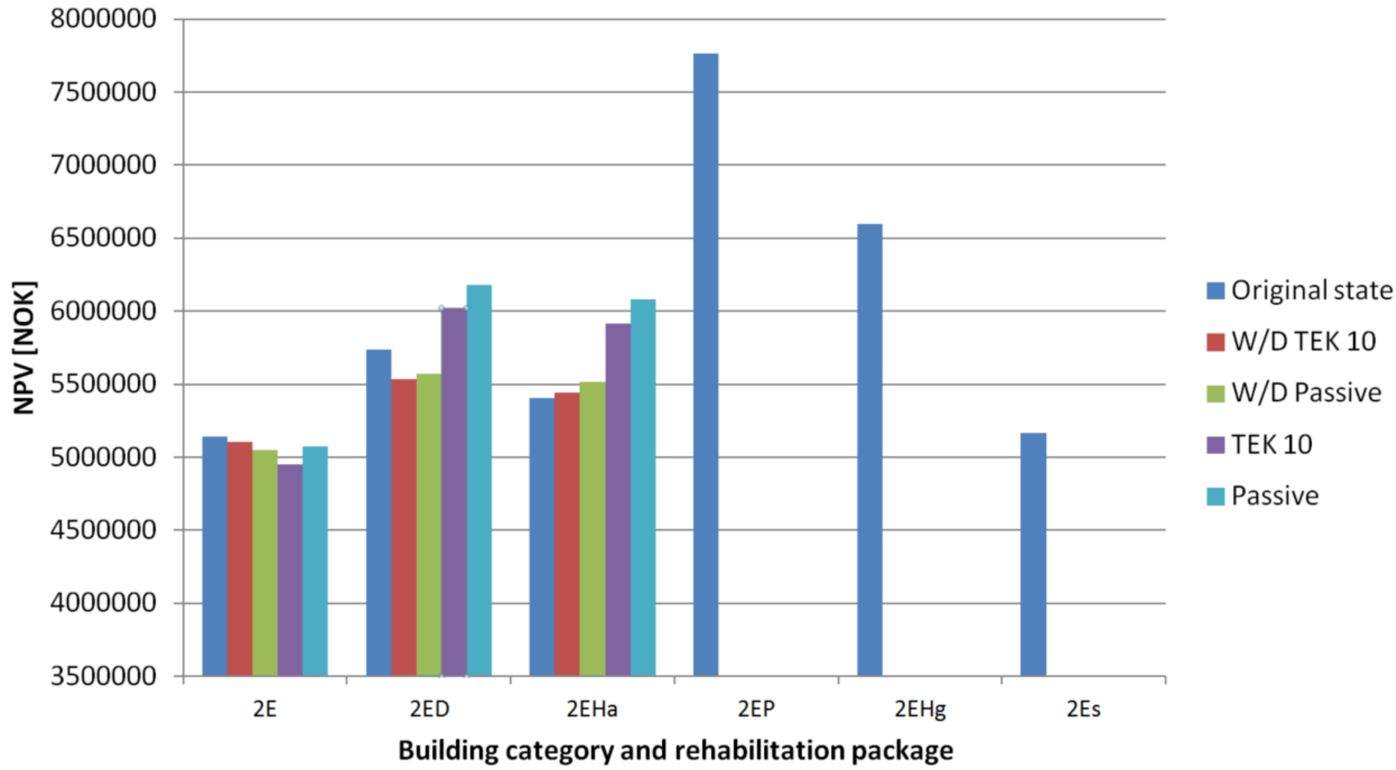

Figure 23: Resulting NPV after cost sensitivity analysis of buildings constructed between 1991 and 2000, assuming a doubling of the energy price for electricity, sorted by original energy source and rehabilitation packages.

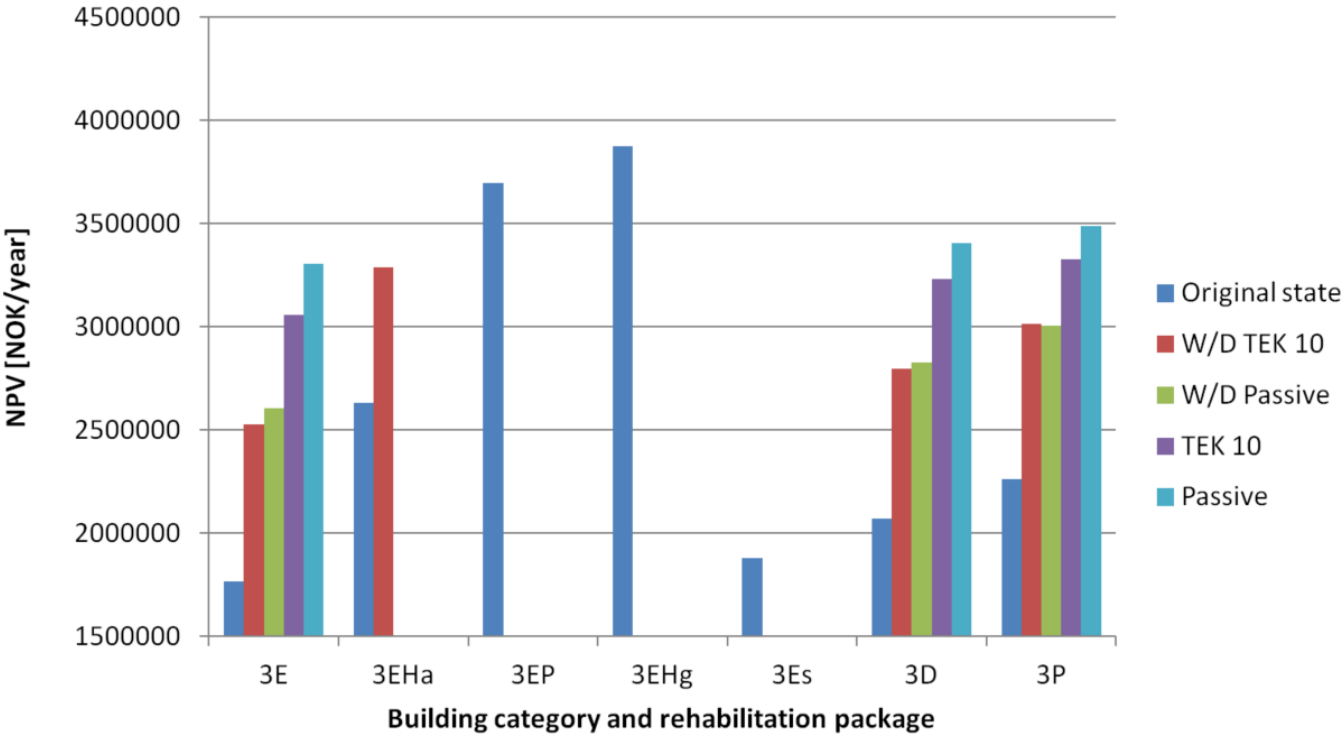

Figure 24: Resulting NPV after cost analysis of buildings constructed between 2001 and 2010 with present costs, sorted by original energy source and rehabilitation packages.

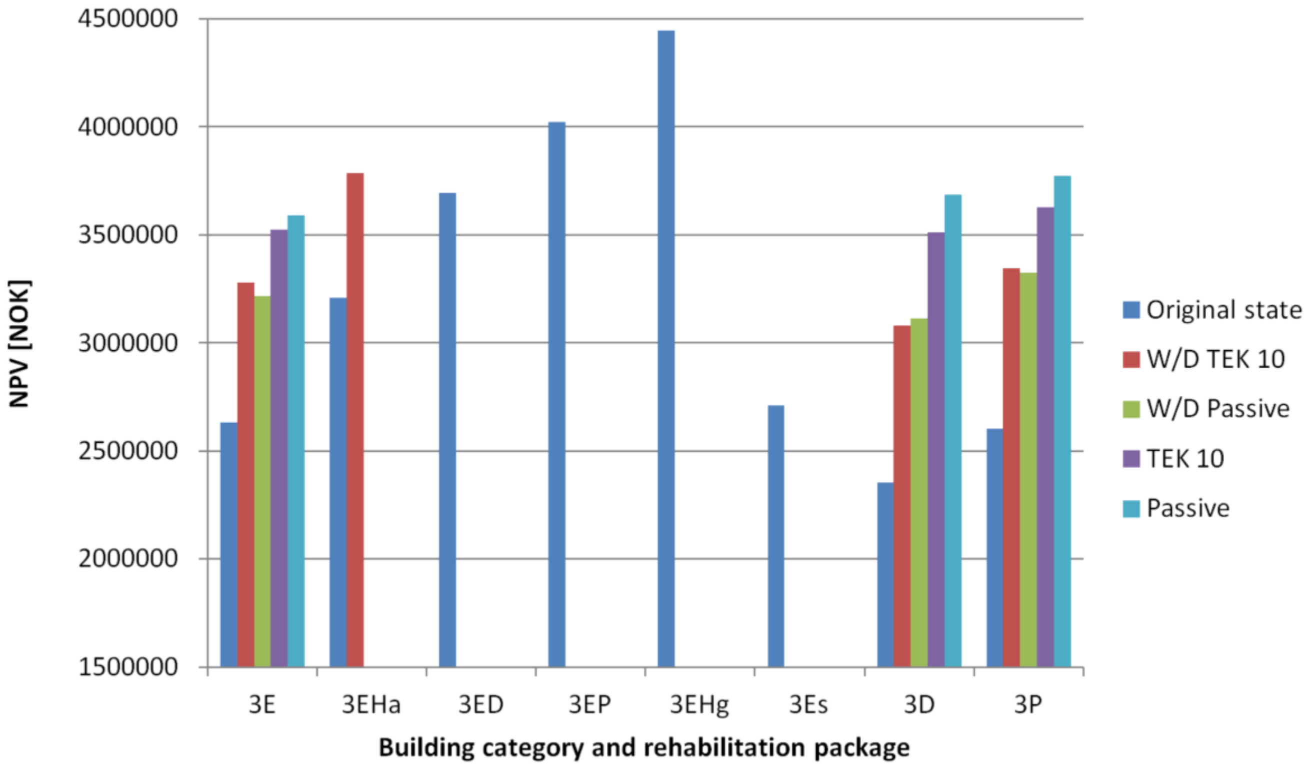

Figure 25: Resulting NPV after cost sensitivity analysis of buildings constructed between 2001 and 2010, assuming a doubling of the energy price for electricity, sorted by original energy source and rehabilitation packages.

4.2.2 Discussion

Main findings

From the results in Fig. 20, it is apparent that buildings with a direct electricity heating system are the cheapest option. The costs can be lowered slightly by replacing windows and doors with TEK 10 standard, but more ambitious rehabilitations will not be profitable. If the heating source is to be changed, for instance in order to fulfil the TEK 10 standard or ensure energy flexibility, air-air heat pumps are the best alternative. This heating system is also more expensive with upgrades leading to lower energy demand. Generally, the installation costs for the systems with hydronic heating are too high to make up for the savings related to lower energy costs. Pellets and district heating are unsurprisingly not a good alternative, as both energy costs and installation costs are higher than for direct electricity. Although district heating systems have the advantage of being able to deliver all heat, removing the necessity of acquiring another heating source, this is not enough for cancelling out the installation costs.

Oil boilers are by far the most expensive alternative. If they are to be replaced, air-air heat pumps are the cheapest alternative, even though the hydronic system can be reused for geothermal heat pumps. High costs for installation of the heat pump and replacement of the hydronic system after its lifetime cancels out the benefits of slightly lower energy prices than the air-air heat pump. It should, however, be emphasised that air-air heat pumps are not suitable for all climates.

The support from Enova does not affect the outcome of the results. However, the support from Enova could be higher, as each project is reviewed individually, and municipality support could also make a difference. Solar heaters are not profitable, but it is possible that a larger solar heater would have lower installation costs per kWh output, as the NPV difference between 1E and 1Es is only around 100,000 NOK.

Higher electricity prices would change the outcome, as seen in Fig. 21. Here, more ambitious rehabilitations result in lower costs for the radiator alternative, and the Passive package is the best alternative. Installing air-air heat pumps also yields lower costs, and this alternative is even better when replacing windows and doors as well with some of TEK 10 standard. Pellets boilers become marginally cheaper than ground-source heat pumps.

Solar heaters are nearly a cost-reducing option, resulting in an NPV only around 14 000 NOK over that of the original building. The differences between the alternatives are generally smaller, but the order of prioritised solutions stay unchanged.

Fig. 22 shows that no rehabilitation strategies will be profitable for buildings from 1991-2000, and the costs generally increase with more ambitious renovations for the electricity options. In the case with district heating, replacing windows and doors is cost-reducing. Similarly to the case with older buildings, pellets is the most expensive alternative, while air-air heat pumps is the best alternative to radiators only. The solar collector does not result in lower costs, as is expected, as the DHW demand is the same for all buildings. All NPVs are lower than for the older building type, as the energy demand is lower.

With a doubling of the electricity price, as seen in Fig. 23, the base case is no longer the cheapest option. Reduced energy yields lower costs, and the TEK 10 alternative is the best. Otherwise, no major changes happen to the preferred order, although the difference between the radiator and air-air alternative is reduced from around 700,000 to 250,000 NOK.

As shown in Fig. 24, the costs of all alternatives are furthered lowered for the newest buildings, as the energy demand is so low. No rehabilitation strategies will lower the costs, and the buildings with electric radiators have the lowest NPV, followed by district heating, and then pellets.[xiv]There is a significant difference between the options where district heating or pellets boiler is kept as an original heating source and where it installed for a building previously heated solely by electrical radiators. This is because the lifetime of these heating systems are defined for such a short timespan that they need to be installed and replaced throughout the period of analysis, while the costs for initial installation has already been covered previously for the cases where the heating system is unchanged. As earlier, the air-air heat pumps alternative is the best option when a building must convert from electric radiators to another heating source.

As seen in Fig. 25, buildings with district heating now have a lower NPV than the buildings with electric radiators (unless the Passive rehabilitation costs are compared). Otherwise, the ranking remains the same.

Comparison to literature

Contradictory to the only study obtained where apartment blocks constructed after 1970 were evaluated separately from the rest of the building stock, the report for Enova by Mjønes et al. (2012), a few rehabilitation strategies were found to be profitable with today's prices (changing windows and doors to TEK 10 standard for 1E and converting from oil boilers to any other alternative heating source). Replacing windows and doors would in this case lead to a TEK 10 standard of the building, which was a criteria for the report. However, by looking at Fig. 20 and considering that only 13 % of 1981-1990 apartments are heated by oil, the potentials for energy with these rehabilitations are small. This study was likely to produce lower NPVs for the rehabilitation project than the Enova report, as the report did not subtract the costs for cladding when this was to be replaced anyway. In the light of this, the results produced here seem realistic. These results suggest that the costs of cladding are large enough to determine whether a rehabilitation project will lower the costs or not.

In contrast to the results in the report by Rambøll and Xrgia (2010), replacing doors and windows is not a profitable measure in most cases. Heat recovery costs were not calculated, but according to this report, and the report by Førland-Larsen (2012), this could be a cost-efficient measure.

As the rest of the studies are conducted on dwellings in general, differences are expected. The studies are divided on the profitability of rehabilitations, but they all agree that retrofit insulation is not cost-efficient, which is in line with the findings in this project. Replacement of windows is pointed out as a recommended strategy by Førland-Larsen (2012), agreeing with the low NPVs of the W/D packages here.

Replacement of cladding, windows, and doors, and adding retrofit insulation to the building envelope, represent an investment cost of around 2.5 to 3 million NOK for TEK 10 or Passive standard, respectively, and this might not even be enough for satisfying NS 3700. Changing windows to TEK 10 standard will cost 1.2 million NOK for 1981-1990 buildings. This is much higher than the costs found by all the reports mentioned in Ch. 2.5. The payback periods found by Dokka et al (2009) are highly optimistic compared to the results found here, but as they are based on higher energy costs, more financial support (both of which contribute to a

[xiv]No calculations have been carried out on this, but it is possible that costs could be lowered by replacing district heating or pellets with electricity radiators only. However, as this is against current policy, this has not been regarded as an option.

lower NPV) and lower discount rate (contributing to higher NPV) it is difficult to compare the values.

Geothermal heat pumps do not seem like a better alternative than air-air heat pumps from these calculations, but this could be caused by the fact that the calculations do not take the differences in ability to provide a larger base load into account. Heat pumps could be a good alternative for apartments with higher energy demand, as their high investment costs and low energy costs will reflect as a better alternatives the higher the energy demand is.

In contrast to Fig. 1, insulation improvements and air-conditioning are not such promising options for this part of Norwegian emissions, as these improvements were found to represent increased costs.

Evaluation of methodology

An LCC requires a large amount of values, and in order to carry through with all calculations, simplifications had to be done. An overview of all simplifications are gathered in App. B.1 and to some extent in Ch. 3.4. As the equations are based on results from the energy balance model, the weaknesses from that model are reflected here.

The model is based on a set rate for top and base load, while this will vary with technology and climate conditions. Air-air heat pumps usually cover 60 % of the energy demand, and not 70 %, while geothermal heat pumps are able to cover more, and also provide cooling when this is needed. These benefits are not reflected by the results.

Other discount rates are used in other projects, and it is possible that another value would lead to more realistic options.

Acquisition costs for heating sources will in many cases be higher than necessary, as the maximum power demand for the unit used in the cost analysis is oversized compared to the actual demand in the various cases.

The energy delivered from the solar collector in this example is small compared to the DHW demand for the building, and a larger solar collector might be a better alternative. Solar collectors were not found to be profitable in any of the cases, but it might have been for a larger system, as it is likely that the costs relative to energy delivered for such as system would be smaller compared to that of a smaller system.

Hydronic heating systems are associated with high costs. As hydronic heating systems are popular in new buildings, this indicates that the acquisition costs are too high and/or the lifetime too short. As this information is gathered from the two main sources, which are assumed to be the most reliable, the costs are kept as they are in order to contain consistency of the costs. It could, however, be possible that an upgrade of the hydronic heating system after the end of its lifetime would be cheaper than installing a brand new one. Based on comparison with other literature, the costs are probably defined as too high for some, or all building parts.

The time of the rehabilitations are not necessarily realistic, especially for the newer cases, as most building components will be far from reaching their lifetimes at that point of time. Replace components that are fairly new and well-functioning is not a usual approach. It would have been better to implement the rehabilitation packages later, or in separate parts, and use a longer time span for the NPV. The time frames and installation years used in the examples are not necessarily based on the most economical outcomes. Other alternatives might be better choices if the rehabilitations were to happen in other years. The implementation years are, however, chosen based on a desire for consistency and for including the long-term effects of various heating systems and rehabilitation choices.

It should be noted that the NPV for the 1O case is higher than what would be realistic, as DHW installation costs are included here.

After conducting all cost calculations, some possible sources for more relevant costs were discovered. This includes installation costs for retrofit insulation at 29.01 NOK/m^2 (Norsk Prisbok 2013), reduction of thermal bridges at 50 NOK/m^2, and air leakage correction at 75 NOK/m^2 (Dokka et al., 2009). (The two last values are calculated based on office buildings, and is possibly not representable.) These costs have not been included in the cost calculation.

The main benefit of the model is that is allows for evaluating all costs in a long-term perspective, whilst taking lifetimes of all building parts into account. The model allows for implementing most of the common energy sources, and separates between buildings of different age, producing more accurate results. Used in a combination with the energy balance model, the cost calculation spreadsheet can be useful for doing quick estimations for evaluating various energy rehabilitations. The spreadsheet is organised such that costs easily can be found, either for certain years, or sorted by installation or energy costs. When input values are changed, this is reflected immediately in the results, allowing for sensitivity analyses or changes to be implemented easily.

Implications and future work

As the costs are the main weakness, work should be carried out for finding more accurate costs. More sensitivity analyses should be conducted in order to understand how various price developments affect the NPV. Predicted future price developments should be included. The calculations should be tested for various time horizons in order to track how these affect the outcome.

When evaluating options that have social or environmental impacts, a cost-benefit analysis, as opposed to an LCC, is the best approach, as non-financial benefits are included. This should be included in further work as a way to integrate both economical and environmental aspects in a single analysis.

Some relevant costs for insulation, air-tightening, and correction of thermal bridges were discovered after the calculations were conducted. These costs can account for up to about 260,000 NOK, and should be included in a re-analysis, as they could change the NPV outcomes.

Based on the present results, energy rehabilitations of apartment blocks from 1981 and later are generally not recommended, financially. If done, they should be combined with general rehabilitations on the outer walls. Oil boilers should be replaced regardless of the regulations, as they are such an expensive option. They should be replaced with direct electricity, or possibly air-air heat pumps. Energy systems beside the oil-based should not be replaced. However, it is important to remember that these calculations represent a standardised building in a set climatic zone, and that a building with different size, thermal envelope, or in a different climatic zone would get completely different recommendations.

If policy makers wish for energy reduction in this dwelling category, financial support must be increased, or stricter regulations must be implemented. However, it is possible that occupants will base their decisions on non-financial reasons, which are further discussed in Chap. 4.3.3.

4.3 Scenario model

4.3.1 Heating systems for further calculations

Based on the results from the energy balance model and cost model, the scenarios examined are chosen as follows:

Business as usual
: Only minimum rehabilitations are conducted: 1E, 1O, 2E, 3E, 3D, 3P

W/D Passive
: The W/D Passive alternatives with the lowest NPV who fulfil the TEK 10 standard are chosen: 1E, 1OHa[xv], 2E, 3E, 3D, 3P

TEK 10
: All buildings are upgraded to fulfil the TEK 10 standard with lowest possible NPV: 1E, 1OHa[xv], 2E, 3E, 3D, 3P

Low costs
: The alternatives with lowest NPVs are chosen: 1E (W/D TEK 10), 1OHa (original state)[xv], 2E (original state), 3E (original state), 3D (original state), 3P (original state)

Low emissions
: The options with the lowest possible emissions are chosen: 1EHg, 1OHg, 2EHg, 3EHg, 3DHg, 3PHg (all TEK 10)

Passive W/D rehabilitations are chosen over Passive rehabilitation, as the energy balance model produced a negative energy demand for these rehabilitations, and these results therefore are assumed to be unrealistic.

Two other scenarios will be used for comparison:

No rehabilitations
: No energy rehabilitations are carried out

ZEB
: Zero energy demand for heating

Neither of these are considered realistic scenarios, but are useful for visualising the minimum and maximum possible energy savings with the defined rehabilitation and demolition rates.

[xv] NPV has not been calculated, but is assumed to be cheapest alternative, based on results from similar calculations.

4.3.2 Results

Figs. 26 - 28 contain outputs from the building stock model by Sandberg et al. (2014) with the inputs described in Ch. 3.5. The number of renovated apartments during the timespan defined for this project for every construction year are visualised in Fig. 26. Fig. 27 visualises the development in demolished apartments.

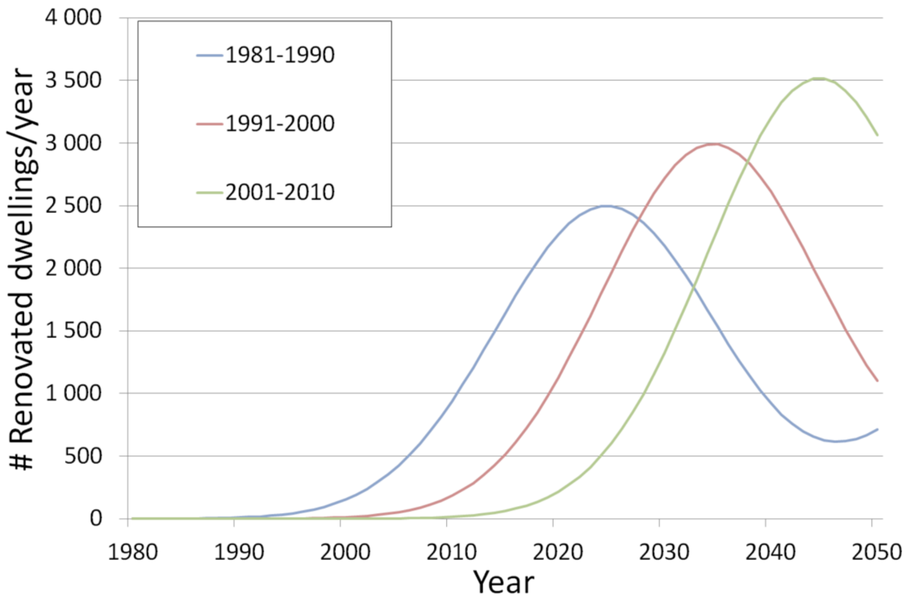

Figure 26: Number of Norwegian apartments constructed between 1981 and 2010 renovated before 2050, sorted by construction year. Simulated using model by Sandberg et al. (2014).

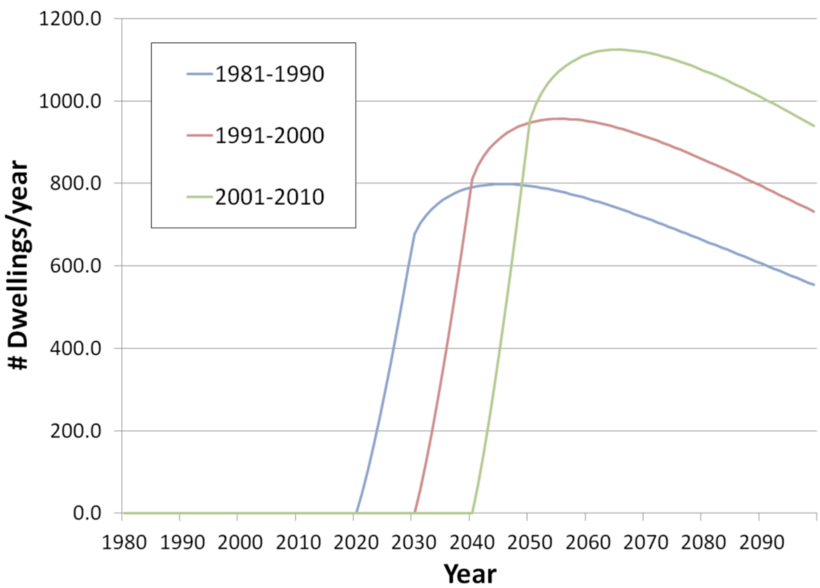

Figure 27: Number of Norwegian apartments constructed between 1981 and 2010 demolished before 2050, sorted by construction year. Simulated using model by Sandberg et al. (2014).

The profiles for renovations and demolition activities in general are collected in Fig. 28. These distributions make up the basis for Figs. 26 and 27, and the Weibull and normal distribution are recognisable.

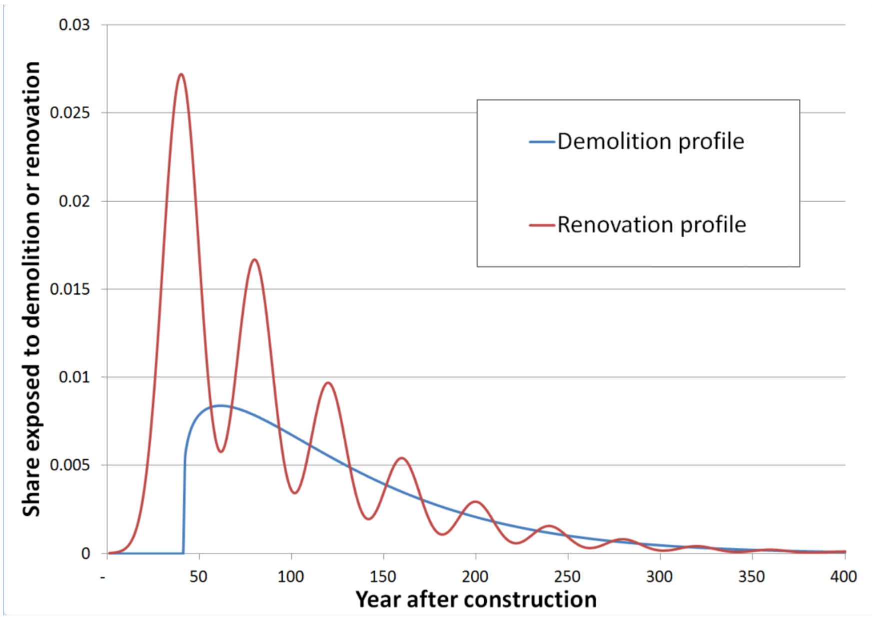

Figure 28: Demolition and renovation profile of Norwegian dwellings, simulated using model by Sandberg et al. (2014).

By combining the results from Figs. 26 and 27 with the construction profiles for apartments defined in the model, the building stock developments as seen in Fig. 29 can be obtained. Here, demolished and rehabilitated apartments have been subtracted from the remaining apartments, resulting in the blue area for original buildings. Based on the output from the building stock model, some apartments should have undergone rehabilitations before 2014, but based on the project definition, rehabilitations before 2014 are not supposed to be a part of the analysis. As the buildings are defined from what is assumed to be their present standard, the rehabilitations before 2014 can be omitted, as it is assumed that any earlier rehabilitations have already affected the average energy demand. The three areas of the graphs are associated with different energy use, and the graphs serve as a basis for all following results.

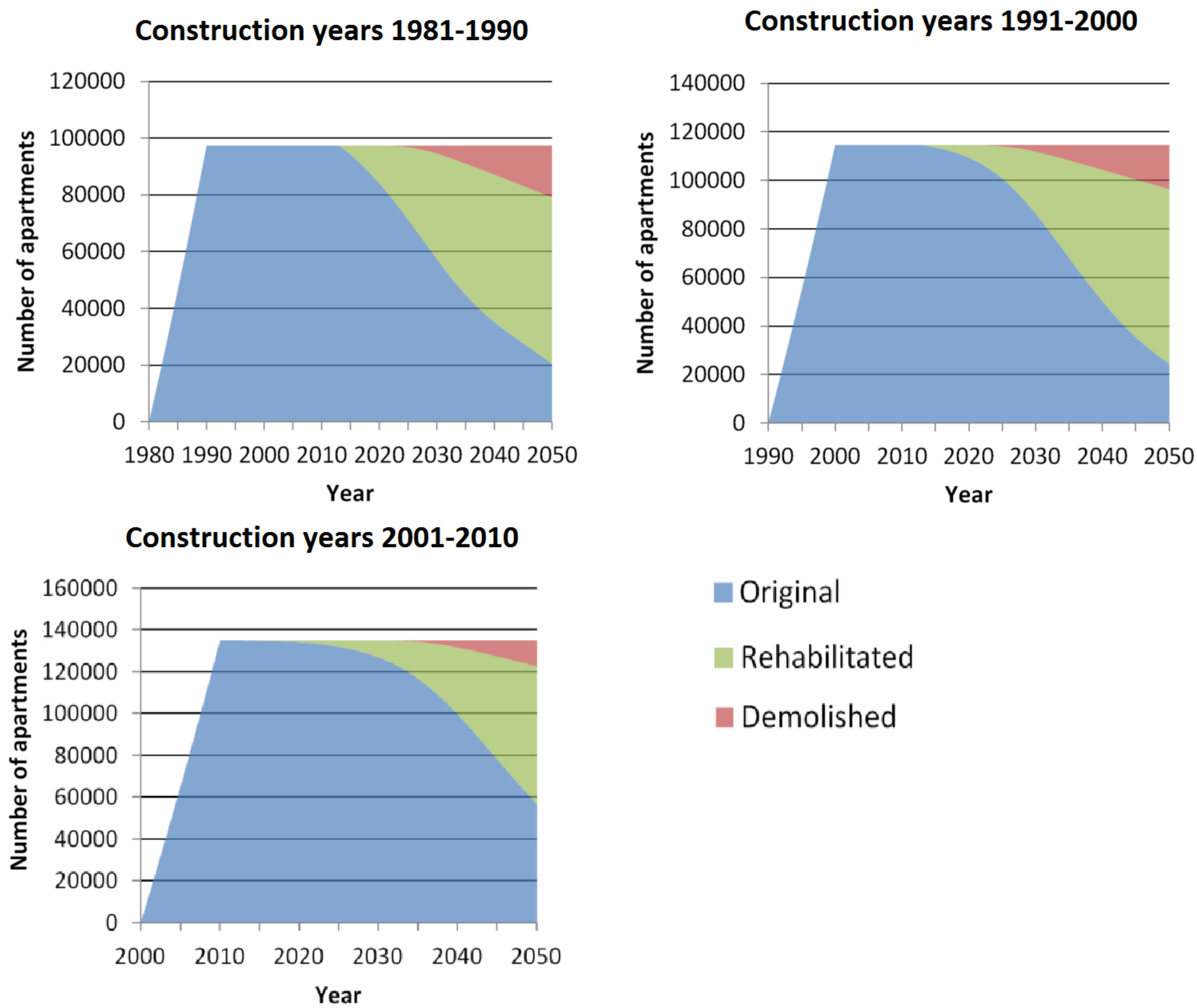

Figure 29: Norwegian apartment stock, constructed between 1981 and 2010. Sorted by original standard, apartments that have undergone rehabilitation, or demolished apartments. Simulated using model by Sandberg et al. (2014).

The dwelling stock development described by Fig. 29 will in total amount to the numbers collected in Table 31. Here, the average yearly rate of renovation and demolition over the time period 2014-2050 are collected as well.

Table 31: Norwegian apartment stock, constructed between 1981 and 2010. Existing in 2014 and subject to renovation or demolition between 2014 and 2050, by amount, share of stock, and average yearly rate.

Building status	Amount	Share of stock	Yearly rate
Apartments in 2014	346574	100 %	-
Rehabilitated within 2050	196477	57 %	1.57 %
Demolished within 2050	48607	14 %	0.39 %

After multiplying the amount of dwellings with different status from Fig. 29 with the energy demand per apartment for the various apartments, as defined in Chap. 4.3.1, the energy demand for all apartments built between 1981 an 2010 will decrease as depicted in Fig. 30. (The development from 1980-2050 can be found in App. C.) The energy demand in 2014 was calculated to 2150 GWh/year, an the final energy demand for the various cases in 2050 are collected in Table 32.

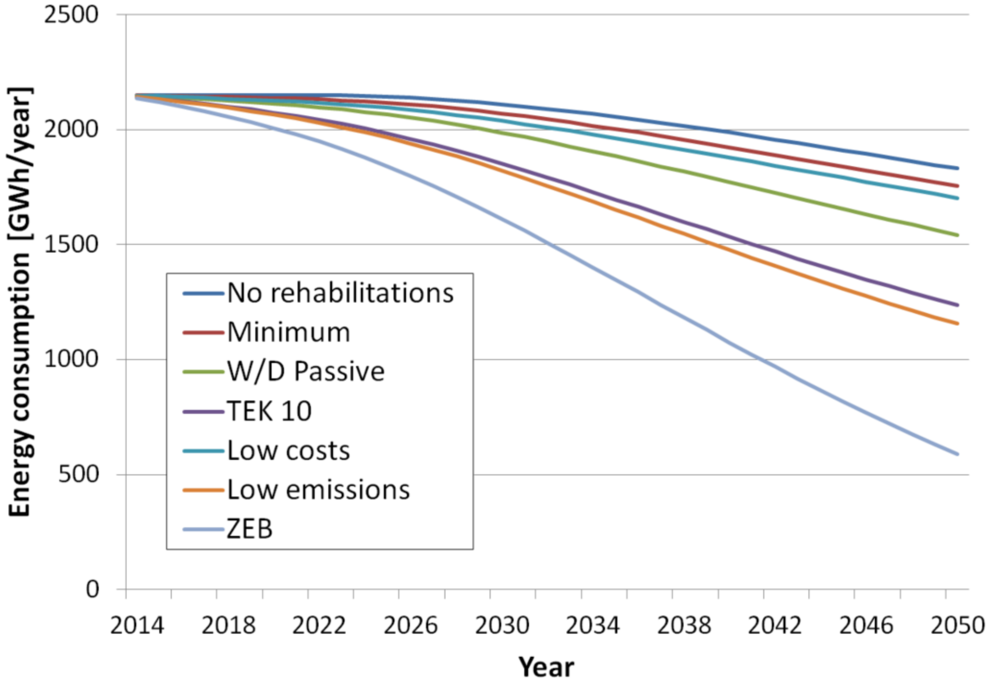

Figure 30: Simulated total energy consumption for heating in Norwegian apartment blocks, sorted by energy scenarios, for the years 2014-2050.

Table 32: Simulated total energy consumption for heating in Norwegian apartment blocks in 2050, sorted by energy scenarios.

Scenario	Energy consumption [GWh/year]	Share of original energy consumption
No rehabilitations	1 831	85 %
Minimum	1 754	82 %
W/D Passive	1 543	72 %
TEK 10	1 236	57 %
Low costs	1 703	79 %
Low emissions	1 155	54 %
ZEB	589	27 %

Combining the total energy development for the defined building stock with the CO_2 emissions connected with the various energy carriers from Tables 12 and 19, a large number of possible CO_2 emission scenarios exist. Figs. 31 - 35 contain some of these possibilities. The results in Fig. 31 are based on Norwegian energy mix, and the final emissions in 2050 are gathered in Table 33.

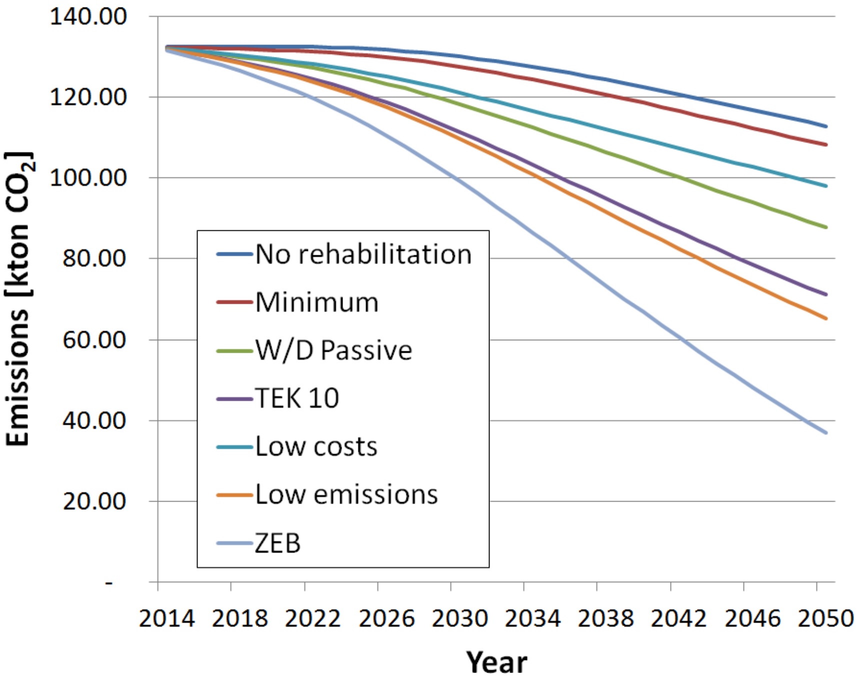

Figure 31: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks 2014-2050, sorted by energy scenarios. Emissions from electricity based on Norwegian mix.

Table 33: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks in 2050, sorted by energy scenarios, compared to the simulated emissions in 2014. Emissions from electricity based on Norwegian mix.

	CO2 emissions [kton]					Share of
Scenario	Electricity	Distr. heating	Oil	Biogenic	Total	emissions in 2014
2014 level	101.24	6.74	12.27	6.5	131.76	100 %
No rehab.	86.50	6.13	14.27	5.91	112.81	86 %
Minimum	82.87	6.13	13.18	5.91	108.09	82 %
W/D Passive	74.72	4.90	3.67	4.53	87.82	67 %
TEK 10	59.67	3.99	3.67	3.74	71.07	54 %
Low costs	82.28	6.13	3.67	5.91	97.99	74 %
Low emissions	56.03	2.84	3.67	2.74	65.27	50 %
ZEB	27.73	2.84	3.67	2.74	36.97	28 %

The emission development in Fig. 32 is based on the Red electricity scenario, which is the electricity scenario with the highest emissions.

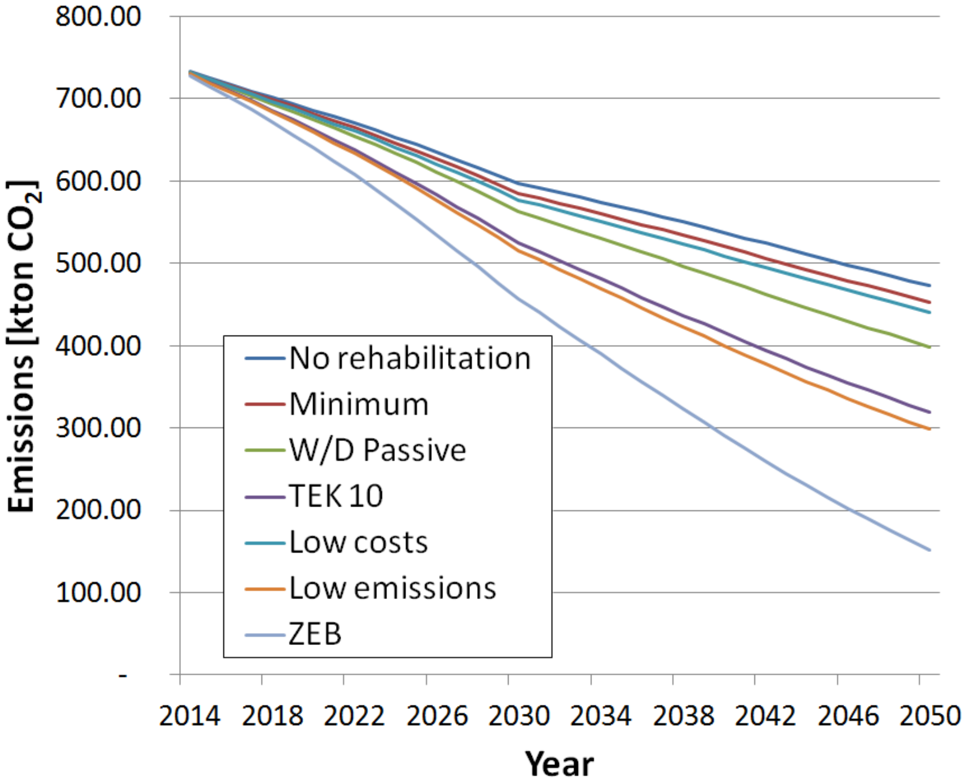

Figure 32: Simulated CO_2 emissions from energy consumption for heating in Norwegian apartment blocks 2014-2050, sorted by energy scenarios. Emissions from electricity based on Red emission scenario.

In Figs. 33 - 35, various electricity scenarios and mixes are tested for a defined scenario: The Low costs scenario for Fig. 33, the Low emissions scenario for Fig. 34, and the TEK 10 scenario for Fig. 35.

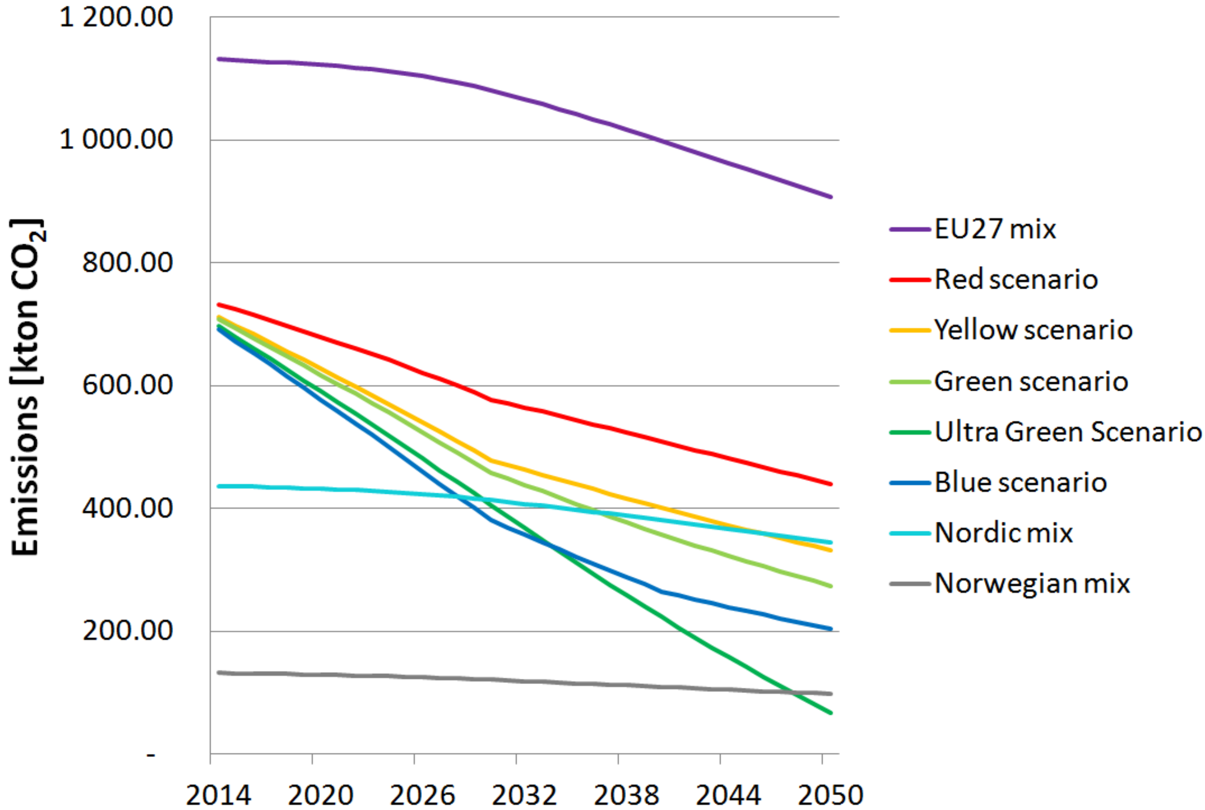

Figure 33: Simulated CO_2 emissions from energy consumption for heating in Norwegian apartment blocks 2014-2050, sorted by electricity mix definitions. Energy consumption based on Low costs scenario.

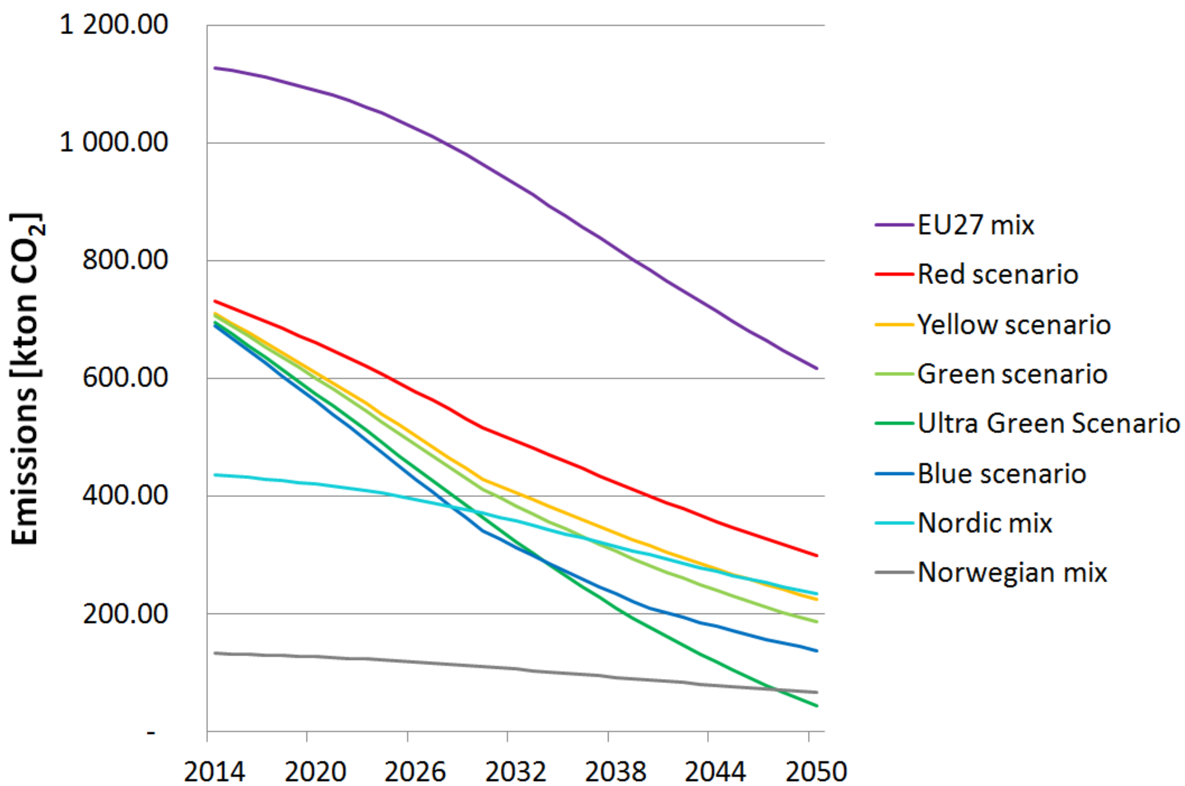

Figure 34: Simulated CO_2 emissions from energy consumption for heating in Norwegian apartment blocks 2014-2050, sorted by electricity mix definitions. Energy consumption based on Low emissions scenario.

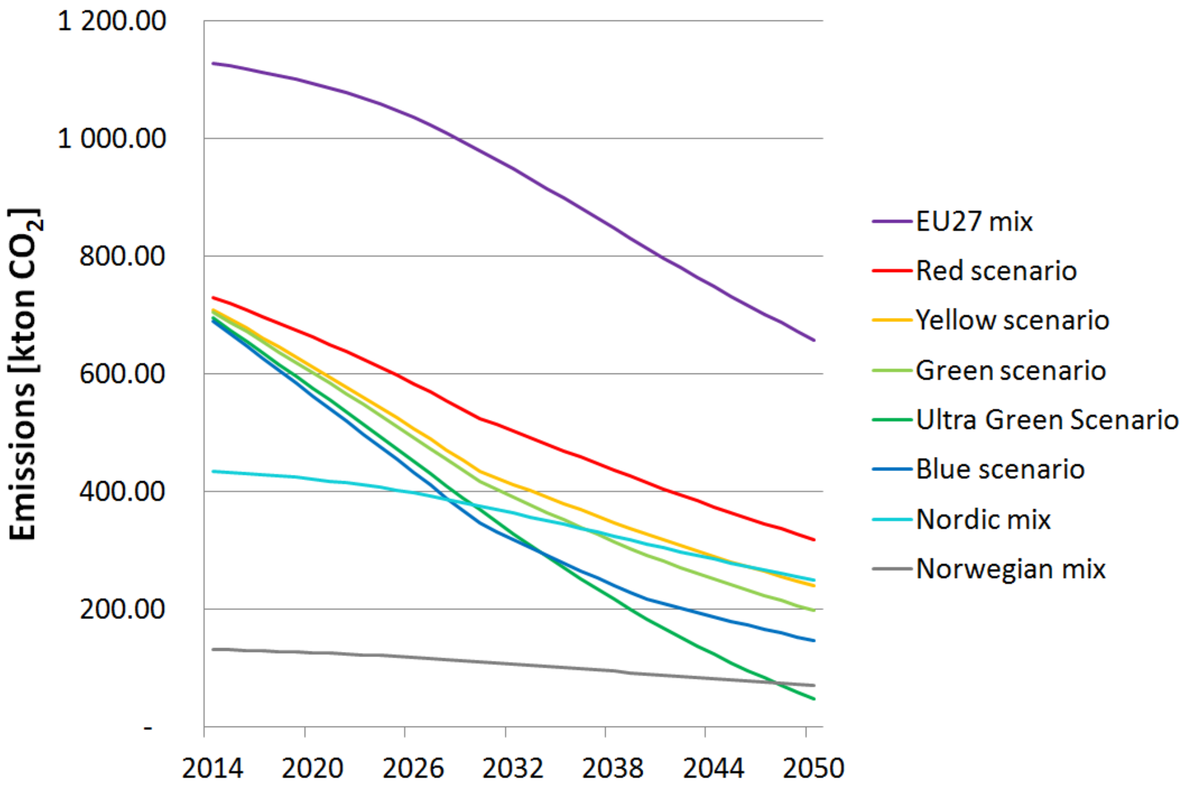

Figure 35: Simulated CO_2 emissions from energy consumption for heating in Norwegian apartment blocks 2014-2050, sorted by electricity mix definitions. Energy consumption based on TEK 10 scenario.

The emissions in 2014 and 2050, and a comparison of these values, for the five scenarios described above are gathered in App. C.

4.3.3 Discussion

Main findings

With the inputs for this project, the building scenario model predicts a long-term development as shown in Fig.28, where the first demolitions happen after 40 years, while the first energy rehabilitations happen only a few years after the construction. The largest share of demolition share occurs early (around 0.7 % of the apartments are demolished at the maximum), and then decreases. After the initial peak after around 40 years, where around 2.7 % of all apartments are rehabilitated, the renovation behaves like a damped oscillating system with amplitudes with wavelengths of 40 years. These behaviours are reflected by Figs. 26 and 27 for all three age groups, although the amplitudes vary according to the number of apartments originally constructed in the various periods of time. The newest buildings make up the largest group, and the oldest makes up the smallest. No demolitions occur before 2014, but rehabilitations start early in the 1990 decennial.

From Fig. 29, it is clear that significant changes will have happened for the apartment stock. Only around 20 % of the apartments constructed between 1981 and 1990 will remain the same as today in 2050, and about the same amount will be demolished. From Fig. 26, it is clear that this building cohort has begun its second renovation wave, possibly connected to a different energy rehabilitation definition. However, as can be seen from Fig. 29, where these renovations are included, the total amount of renovated dwellings is lower than the total amount of unchanged buildings. Therefore, these rehabilitations can be included without causing problems.

Fig. 30 and Table 32 reveal that energy rehabilitations can make a great impact on the energy consumption, although this depends entirely on the rehabilitation packages chosen. Demolitions alone will result in a 15 % lower energy consumption in 2050 for this particular building stock, and an additional 3 % is expected to occur based on the minimum rehabilitations. If only the rehabilitations related to lowered costs are implemented, the energy will be reduced by 21 %, which is only 3 % less than the defined minimum case. TEK 10 energy demands will probably result in an energy consumption around this value as well, as buildings newer than 1990 already are assumed to fulfil the standard, and the older buildings require only minor rehabilitations in order to fulfil the requirements. However, the outcome could be greatly altered if the energy sources were switched to heat pumps. When following the TEK 10 component requirements, the energy is reduced by 43 %, and the low emissions scenario leads to a reduction of 46 %. If energy renovations lead to an energy consumption of 0 kWh/year for heating purposes, the energy reduction would have been 73 %.

Based on Norwegian electricity mix, emission reductions follow a similar development as for the energy consumption, although generally a little lower. The Low emissions scenario results in a 50 % reduction. In comparison, ZEBs would lead to a 72 % reduction, while minimum rehabilitations would reduce the emissions by 18 %. The emissions are 132 kilotons CO_2 in 2014 when based on Norwegian electricity mix, but over five times higher when the Red energy scenario is used as a basis. When comparing Figs. 31 and 32, it is clear that the emission development for the Norwegian electricity mix matches the energy reduction closer than the development predicted with the Red scenario. As the Red scenario is based on a reduction of CO_2 emissions from electricity production, the relative emission reductions are higher than for the Norwegian scenario (about 34 % with no rehabilitations and 60 % for the Passive scenario). However, even when following the ZEB scenario, the emissions will be higher in 2050 based on the Red electricity scenario than when based on the Norwegian electricity mix in 2014.

The three last figures visualise the differences in emission outcomes for various electricity definitions. Clearly, the definitions for electricity emissions are of a much higher importance than the rehabilitation scenarios when predicting the total emissions. EU27 mix is the highest of all, but also make for the greatest saving potential. This electricity mix is usually not used as a basis when estimating emissions from Norwegian electricity consumption, but it does serve as an explanation as to why energy reduction in building is prioritised more heavily in the EU than in Norway. Norwegian mix serves as the lowest emissions alternative until a few years before 2050, when the Ultra Green scenario is assumed to reach lower emission levels. The emission reductions with Norwegian electricity mix are almost indistinct compared to the great savings connected with the Ultra Green scenario, where the emissions are reduced from almost 700 kilotons CO_2 in 2014 to around 50 in the Low emissions scenario.

Comparison to literature

Comparing the results in this project to literature is not an easy task, as to the author's knowledge, few studies exist on the predicted energy use and emissions from such a limited part of the dwelling stock.

The reports assuming linear development in renovation and demolition defined demolition rates between 0.1 % and 0.6 %, and an energy rehabilitation rate of 2 %. Comparatively, the average rates produced by the dwelling stock model are 0.39 % and 1.57 %, respectively. However, these rates are defined for a limited part of the dwelling system over a short period of time, and the values cannot be compared accurately.

The report by Hille et al. (2011) is the only source found for the energy development of existing buildings, specifically. Their estimation of 94.3 kWh/m^2 in 2009 to 81 kWh/m^2 in 2030 represents a reduction of 14 % over 21 years. Comparing this scenario to the values in 2035 in Fig. 30, it seems to match the W/D Passive scenario. The other reports vary greatly in terms of energy predictions, as they include buildings to be constructed in the future. If TEK 15 sets Passive requirements to new buildings, it can be assumed that new buildings, even when taking high population and population per dwellings scenarios into account (the highest prognosis in Figs. 12 and 14), should not contribute to higher energy consumption, as passive house dwellings have such low energy use. Fig. 16 and most other reports supports this reasoning, but it is likely that these studies have not taken increased requirements into account.

If existing buildings are to reach the energy reduction target set by Arnstad (2010), neither of the defined scenarios will be good enough if its is assumed that the energy consumption has been stable from 2010, as the energy consumption must be reduced by 12.5 % by 2020. If this target is shifted to involve a reduction of 12.5 % from 2014 to 2024, the reduction is only possible with the ZEB scenario. However, the energy reduction potentials are higher in older buildings and single housings, and it is realistic to expect that the reduction share required of apartments built between 1981 and 2010 are not expected to lower their energy consumption this much. Reaching the last government target of 15 TWh energy reduction from 2012 to 2020 means an energy reduction of around 19 % over 8 years. This requires an average decrease in energy demand of 2.35 %, which is even higher than the target defined by Arnstad (2010).

The graphs in Fig. 30 show steeper reductions over time, because of the shape of the rehabilitations curves and the increasing number of demolsished buildings. Energy targets with set reduction rates will therefore be easier to reach with longer time periods.

Table 18 suggests that future buildings will utilize a greater variety in energy systems than what has been chosen for testing in Chap. 4.3.1. The high shares for district heating, water-air heat pumps, wood, and other bioenergy is not supported by the results in this report. If these energy sources become increasingly popular for buildings with low energy demands, this could affect the CO_2 emissions significantly.

The emissions from the Norwegian dwelling stock do not seem to be able to match the EU goal of 20 % reduction from 2005 to 2020 when looking at the development of the previous energy consumption in Fig. 5 and the predictions for emissions from Fig. 18. A 20 % reduction from today and over the next 15 years is possible for this dwellings stock only in the ZEB case. If the Red emission scenario (Fig. 32) is used as a basis, the W/D Passive alternative is enough for reaching these goals, as the scenario assumes lower emissions for electricity production over time.

The results from this report do not follow the same pattern as Fig. 18, which is the scenario for the total building stock. The reasons for this can be many, and some of the possibilities include the expected increase of future building area, and that energy rehabilitations for the entire dwelling stock is a long-term project. The expected development in this project is possibly less realistic.

Evaluation of methodology

A thorough evaluation on the dwelling stock model is not a task for this project, as a paper on its details is being written by Sanberg et al. (2014). However, Fig. 14 shows that it fits fairly well with statistical data. The model is able to produce a more detailed future stock development, and is able to separate between defined building groups. These advantages make this model a better basis for energy and emission rehabilitations than if the calculations were to be done with linear growth, rehabilitation, and emission rates. If the model were to be adapted in order to show separate rehabilitations at once, and also show what kind of buildings (original, subject to rehabilitation 1, subject to rehabilitation 2 and so on) that are demolished, this would make it even more suitable for an analysis like this in the future.

The reliability of the results depend on the reliability of the energy balance model, the cost calculation, and the dwelling stock model, and these have already been discussed. Evaluation by comparison is not possible on a detailed level, as the related literature is concerned with larger parts of the building stock.

User behaviour has not been evaluated in the scenario models, and this represents a large factor of uncertainty. Costs and emissions are only two reasons for rehabilitation, and the benefits could be cancelled out by increasing the temperature or by choosing an energy system unfit for the local outdoor climate. It is possible that energy consumption will be taken into consideration to a larger degree, now that the energy consumption for all buildings sold must be labelled through the Energy grading system.

As mentioned several times, the buildings are stereotypical, not average buildings, and based on a set climatic zone. The accumulated potentials for these buildings do not necessarily represent the total potentials for this building stock. Some renovations are done earlier than 2014, and these are omitted in the calculations.

Simplifications include that only non-rehabilitated buildings are assumed to be demolished, that only one type of energy rehabilitation can be conducted over the evaluation period, that all buildings are rehabilitated to the same energy target, and that buildings with a certain energy system all undergo the same type of rehabilitation. The method does not include all energy and emissions connected to the rehabilitations, such as those related to production and demolition of construction parts, etcetera.

The strength of the model is its potential for accuracy: Population development, rehabilitations, demolitions, and average areas are modelled dynamically, and the model is able to take both energy reduction and several heating sources as inputs, returning a large amount of data for a defined part of the building system. If based on accurate information, this methodology is expected to be very useful for assessing energy and emission targets and regulations.

Implications and future work

The results imply that emissions and energy consumptions for this particular building stock will not be significantly reduced, compared to the minimum alternative, if rehabilitations are done with costs in mind. If the emissions and energy consumption is to be lowered, the standardised financial support from Enova can be increased in order to make options pay off, benefits besides cost reduction can be emphasised for decision-makers, or stricter building standards can be enforced. Some factors, such as increased electricity price or changes in emissions from the various energy carriers can also affect the outcome.

The definition of electricity emissions has a higher influence on the final emission outcome than the rehabilitation packages themselves. A standardised emission for calculations like these would be beneficial for comparing studies, as some are based on zero emissions electricity. In order to find the optimum rehabilitation strategy, clear energy targets for apartment blocks must be set by Norwegian policy makers.

The TEK 10 requirement for rehabilitations does not cause major energy reductions, but the Passive standard can reduce the energy consumption significantly. Setting this as a requirement for the TEK 15 standard seems like a good idea for this building stock if energy reduction is to be a priority. However, energy consumption for these buildings must probably be evaluated with a different model than TABULA.

Establishing which of the emission scenarios that should be prioritised is difficult, as there are no such current Norwegian targets for the building stock. When comparing with EU targets, these could be reached with D/W Passive rehabilitations or more ambitious ones, depending on the emission definition of electricity. When basing the emissions on EU27 electricity mix, the saving potential is even greater. Based on this, as well as the fact that Norway has the lowest CO_2 emissions per useful floor area in Europe, and that this part of the dwelling stock already is associated with low energy consumption and emissions per m^2, ambitious targets as the one set by the EU do not seem to be suited for this building stock.

In order to increase the reliability of the model, more information should be gathered on rehabilitation preferences, costs, and building statistics, as mentioned in previous discussions.

Several alternative scenarios should be investigated, as they might serve as more beneficial strategies or shed light on more aspect of the current regulations:

- TEK 10 energy requirements and energy source requirements, representing the energy demand and emissions from apartments upgraded to the lowest possible standard within the TEK 10 requirements.
- W/D Passive rehabilitations with no rehabilitations to the energy system, representing another low effort option
- Passive rehabilitation based on NS 3700 energy requirements. The Passive requirements in this project was chosen to match a higher level than necessary, producing energy demands so low that they were deemed unrealistic.
- Including removal of all fuel oil boilers in 2020, as is mandatory.
- Rehabilitations that vary over time, causing increasingly higher energy reductions, such as done by Arnstad (2010).
- An option based on ventilation upgrades only. In retrospect, this alternative could prove to be very relevant for upgrades, as ventilation upgrade costs generally are low compared to retrofit insulation and windows.

5 Conclusion

In this project, energy consumption in original and rehabilitated standardised apartment blocks constructed between 1981 and 2010 were investigated using the TABULA energy balance model. Rehabilitation costs were calculated based on life cycle assessment cost principles, and the future energy and emissions for this building stock were calculated with a model from the Industrial Ecology Programme at NTNU.

The buildings have a fairly low energy demand for heating, compared to other dwellings. Results from the calculations show that apartment blocks built after 1990 already fulfil the TEK 10 maximum energy targets. The buildings constructed between 1981 and 1990 can achieve the targets by replacing doors and windows with TEK 10 standard components. The energy balance results in this report generally produce lower energy demand than the consensus values, suggesting that the energy saving potentials are higher in reality. The results match better for the buildings with high energy use, but the results produced for passive house rehabilitations are deemed unrealistic. This is probably caused by the building components being defined in too high quality, and shortcomings of the TABULA model. If the TABULA model is edited to include overheating, it would provide better results for cases like these.

Buildings with electric radiators are the cheapest air heating source for all buildings. For buildings constructed between 1981 and 1990, costs can be lowered slightly by replacing windows, but more ambitious renovations are not profitable. If the energy source is to be changed in accordance to TEK 10, air-air heat pumps seem like the best alternative for buildings of all ages. However not profitable, other systems could be preferable for energy flexibility or comfort. Oil boilers are the most expensive alternative by far, and should be phased out regardless of energy or environmental concerns. No rehabilitations were profitable for buildings from between 1990-2010, except when district heating is the installed heating system. The support from Enova does not affect the outcomes of the results in these cases, and financial support or stricter regulations are necessary if ambitious rehabilitations are desired. Doubling of the electricity price would make air-air heat pumps the best option for 1980 decennial buildings, and increased insulation profitable for 1990 century buildings.

40 year rehabilitations and standard demolition values in the building stock model produces 57 % rehabilitations and 14 % demolitions within 2050. Demolitions alone result in a lowered energy demand of 15 % within 2050, while the scenario based on lowest possible costs results in 21 %. The low emissions case result in a 50 % reduction, while rehabilitations to zero energy buildings would lead to 72 %. Emissions follow similar paths as for the energy consumption when Norwegian electricity mix is used as a basis. However, definitions on electricity mix and related emissions matter more than the energy rehabilitations when describing emissions.

No official regulation is presently set for Norway, although a report for the former Government expressed a target of 50 % energy reduction between 2010 and 2040. This target cannot be met by the renovations as defined here, although it is possible to reach with zero energy upgrades. However, it is not reasonable to expect this building group to reduce energy and emissions by the same share as most other buildings. The TEK 10 standard will not reduce the emissions or energy significantly, but the Passive standard has high potentials.

Further work should include calculations on redefined packages. More information is needed on rehabilitation preferences, costs, building statistics, and climatic zone variations. Other installation years should be tested for the cost calculations.

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Appendix

A Energy balance details

A.1 Abbreviations defined by TABULA

Quantity	Explanation	Unit	Chapter
$a_{H,0}$	constant parameter standard value for the seasonal method: $a_{H,0}$ = 0.8 (according to EN 13790)	[-]	2.5
$\alpha_{nd,h,i}$	fraction of heat generator i used for space heating	[-]	3.2
$\alpha_{nd,w,i}$	fraction of DHW heat generator i	[-]	3.1
ΔU_{tbr}	surcharge on all U-values, taking into account the additional loses caused by thermal bridging	[W/(m²K)]	2.2
$\eta_{h,gn}$	dimensionless gain utilization factor	[-]	2.1
φ_{int}	average thermal output of internal heat sources	[W/m²]	2.4
$\eta_{h,gn}$	dimensionless gain utilization factor,	[-]	3.2
$\eta_{ve,rec}$	efficiency of ventilation heat recovery (weighted average during heating season)	[-]	3.2
$\vartheta_{e,b}$	heating base temperature	[°C]	6
$\overline{\vartheta_{e,hs}}$	temperature of the external environment (average value during heating season)	[°C]	2.1
$\overline{\vartheta_{e,i}}$	temperature of the external environment, average value for the respective day i	[°C]	6
ϑ_{int}	internal temperature (set-point temperature for space heating)	[°C]	2.1
τ	time constant of the building (see below)	[h]	2.5
$\tau_{H,0}$	is a constant parameter standard value for the seasonal method: $\tau_{H,0}$ = 30 h (according to EN 13790)	[h]	2.5
$\tau_{H,0}$	is a constant parameter standard value for the seasonal method: $\tau_{H,0}$ = 30 h (according to EN 13790)	[h]	2.5
$A_{C,extdim}$	conditioned floor area based on external dimensions	[m²]	7
$A_{C,intdim}$	conditioned floor area based on internal dimensions	[m²]	7
$A_{C,living}$	conditioned living area	[m²]	7
$A_{C,ref}$	reference area of the building	[m²]	2.3, 2.4, 7
$A_{C,use}$	conditioned useful floor area	[m²]	7
$A_{window,j}$	area of all windows with orientation j	[m²]	2.4
b_{tr}	adjustment factor soil	[-]	2.2

c_h c_w	annual energy costs for space heating and domestic hot water	[€/(m²a)]	4.3
c_m	internal heat capacity per m² reference area	[Wh/m²K]	2.5
$c_{p,air}$	volume-specific heat capacity of air	[Wh/(m³K)]	2.3
d_{hs}	length of the heating season expressed in days	[d/a]	2.1, 2.4, 6
d_i	duration of day i = 1 d i index of the days of a year	[d]	6
$e_{g,h,i}$	heat generation expenditure factor of heat generator i used for space heating	[-]	3.2
$e_{g,w,i}$	heat generation expenditure factor of DHW heat generator i	[-]	3.1
$A_{env,i}$	area of envelope element i	[m²]	2.2
$f_{adapt,k}(q_{del})$	adaptation factor of type k, as a function of the delivered energy q_{del} (sum of energywares without auxiliary electricity) determined by standard calculation method	[-]	5
$f_{co2,aux}$	carbon dioxide emission factor of electricity used for auxiliary devices	[g/kWh]	4.2
$f_{co2,h,i}$ $f_{co2,w,j}$	carbon dioxide emission factors of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[g/kWh]	4.2
F_F	frame are fraction of the windows	[-]	2.4
F_{nu}	dimensionless correction factor for non-uniform heating, taking into account systematic deviations of the set-point temperature and the actual average temperature (time average over night and day as well as space average over living areas and reduced or indirectly heated spaces)	[-]	2.1
$f_{p,nonren,aux}$	non-renewable primary energy factor of electricity used for auxiliary devices	[-]	4
$f_{p,nonren,h,i}$ $f_{p,nonren,w,j}$	non-renewable primary energy factors of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[-]	4.1
$f_{p,total,aux}$	total primary energy factor of electricity used for auxiliary devices	[-]	4.1
$f_{p,total,h,i}$ $f_{p,total,w,j}$	total primary energy factors of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[-]	4.1
F_{sh}	reduction factor external shading	[-]	2.4
F_W	is a reduction factor, considering radiation non-perpendicular to the glazing	[-]	2.4
$g_{gl,n}$	total solar energy transmittance for radiation perpendicular to the glazing	[-]	2.4

$h_{room,ve\ ref}$	ventilation reference room height	[m]
H_{tr}	overall heat transfer coefficient by transmission	[W/K]
h_{tr}	heat transfer coefficient by transmission per m² reference floor area	[W/(m²K)]
h_A , h_B	are constants, depending on the building type	[W/(m²K)]
H_{ve}	total heat transfer by ventilation	[W/K]
$I_{Sol,j}$	average global irradiation on surfaces with orientation j during the heating season	[m²]
$I_{sol,k,hs}$	global solar radiation on 1 m² surface of orientation k during the heating season	[kWh/(m²a)]
$I_{sol,k,i}$	global solar radiation on 1 m² surface of orientation k during day i	[kWh/(m²d)]
k	orientation of a transparent surface	[-]
$m_{co2,h}$ $m_{co2,w}$	annual carbon dioxide emissions for space heating and domestic hot water	[kg/a]
$n_{air,infiltr}$	air change rate by infiltration	[1/h]
$n_{air,use}$	average air change rate during heating season, related to the utilisation of the building	[1/h]
p_{aux}	price of electricity used for auxiliary devices	[€/kWh]
$p_{h,i}$ $p_{w,j}$	prices of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[€/kWh]
$q_{del,h,adapt,i}$ $q_{del,w,adapt,j}$	expectation value of the measured consumption for space heating and DHW	[kWh/(m²a)]
$q_{del,h,adapt,i}$ $q_{del,w,adapt,j}$	annual energy use of heat generator i of the heating system and of heat generator j of the hot water system per m² reference floor area, adapted to the typical level of measured consumption	[kWh/(m²a)]
$q_{del,h,aux}$ $q_{del,w,aux}$	annual auxiliary energy use of heat generator i of the heating system and of heat generator j of the hot water system per m² reference floor area	[kWh/(m²a)]
$q_{del,h,i}$ $q_{del,w,j}$	annual energy use (delivered energy) of heat generator i of the heating system and of heat generator j of the hot water system per m² reference floor area, calculated by applying the standard boundary conditions	[kWh/(m²a)]
$q_{d,h}$	annual effective heat loss of the space heating distribution system per m² reference floor area	[kWh/(m²a)]
$q_{d,w}$	annual heat loss of the DHW distribution system per m² reference floor area	[kWh/(m²a)]
$q_{d,w,h}$	recoverable heat loss of the DHW distribution system per m² reference floor area	[kWh/(m²a)]

$q_{g,h,out}$	heat output of heat generator i used for space heating	[kWh/(m²a)]
$q_{g,w,h}$	recoverable heat loss of the DHW heat generators per m² reference floor area	[kWh/(m²a)]
$q_{g,w,out}$	heat output of DHW heat generator i	[kWh/(m²a)]
$Q_{H,gn}$	total heat gains for the heating mode	[kWh/a]
$Q_{H,nd}$	building energy need for heating, assumed to be greater than or equal to 0	[kWh/a]
Q_{ht}	total heat transfer for the heating mode	[kWh/a]
$Q_{ht,tr}$	total heat transfer by transmission during the heating season	[kWh/a]
$Q_{ht,ve}$	total heat transfer by ventilation during the heating season	[kWh/a]
$q_{ht,ve}$	annual heat transfer by ventilation per m² reference floor area	[kWh/(m²a)]
$q_{nd,h}$	annual energy need for heating (useful heat) per m² reference floor area	[kWh/(m²a)]
$q_{nd,w}$	annual energy need for domestic hot water (useful heat) per m² reference floor area	[kWh/(m²a)]
$q_{p,nonren,h}$ $q_{p,nonren,w}$	non-renewable primary energy demand for heating and hot water	
$q_{p,total,h}$ $q_{p,total,w}$	total primary energy demand for heating and hot water	[kWh/(m²a)]
$q_{s,h}$	annual effective heat loss of the heating system storage per m² reference floor area	[kWh/(m²a)]
$q_{s,w}$	annual heat loss of the DHW storages per m² reference floor area	[kWh/(m²a)]
$q_{s,w,h}$	recoverable heat loss of the DHW storages per m² reference floor area	[kWh/(m²a)]
$q_{w,h}$	recoverable heat loss of the DHW system per m² reference floor area	[kWh/(m²a)]
$q_{ve,h,rec}$	space heating contribution of the ventilation heat recovery unit per m² reference floor area	[kWh/(m²a)]
$R_{0,i}$	thermal resistance of the envelope element i in the original state, calculated according to EN ISO 6946	[m²K/W]
$R_{add,i}$	additional thermal resistance due to unheated space bordering at the construction element i	[m²K/W]
$R_{eff,i}$	effective thermal resistance of the envelope element i	[m²K/W]
$R_{measure,i}$	(additional) thermal resistance of a thermal refurbishment measure applied to the element i in case of a simple insulation measure (additional layer of	[m²K/W]

	insulation) $R_{measure,i}$ is calculated by a quotient of the insulation thickness $d_{ins,i}$ and the thermal conductivity $\lambda_{ins,i}$; in other cases (e.g. in case of insulation between rafters) the thermal resistance is calculated by the rules of EN ISO 6946	
$U_{0,i}$	U-value of the envelope element i in the original state, calculated according to EN ISO 6946	[W/(m²K)]
$U_{eff,i}$	effective U-value of the envelope element i	[W/(m²K)]
V_C	conditioned building volume	[m³]

Source: Loga and Diefenbach (2012a)

A.2 Values chosen for all energy balance calculations

Table 34: Vales chosen for all energy balance calculations used as a basis for cost calculation.

Abbreviation	Value	Source
y	$\dfrac{Q_{sol}+Q_{int}}{Q_{ht,ve}+Q_{ht,tr}}$	TABULA equation
a_H	$a_{H,0}+\dfrac{t}{t_{H,0}}$	TABULA equation
$a_{H,0}$	0.8	TABULA standard value
$A_{window,hor}$	0	Assumption
$A_{window,east}$	0	Mjønes et al., 2012, p. 56
$A_{window,west}$	0	Mjønes et al., 2012, p. 57
$A_{window,door}$	14.4	Assuming 6 large doors, satisfying TEK 10, § 12-15 for height and width
$\alpha_{nd,h,1}$	1	Assuming no loss
$\alpha_{nd,h,2}$	0	Assuming one heating source
$\alpha_{nd,h,3}$	0	Assuming one heating source
$\alpha_{nd,w,1}$	1	Assuming no loss
$\alpha_{nd,w,2}$	0	Assuming one heating source
$\alpha_{nd,w,3}$	0	Assuming one heating source
$b_{tr,ext}$	1	TABULA standard value
$b_{tr,unh}$	1	TABULA standard value
$b_{tr,cellar}$	0.5	TABULA standard value
$b_{tr,soil}$	0.5	TABULA standard value
c_m	45	TABULA standard value
$c_{p,air}$	0.34	Standard value
d_{hs}d_hs	237	Enøk normtall, p. 63
$e_{g,h,1}$	1	Institut Wohnen und Umwelt GmbH, 2013b, Danish value
$e_{g,h,2}$	0	Assuming one heating source
$e_{g,h,3}$	0	Assuming one heating source
$e_{g,w,1}$	1	Institut Wohnen und Umwelt, 2013b, assuming same value as "electric heat panels" (DK) and "electric heating rod"(DE)
$e_{g,w,2}$	0	Assuming one heating source
$e_{g,w,3}$	0	Assuming one heating source
F_{sh} (horizontal orientation)	0.8	TABULA standard value
F_{sh} (vertical orientation)	0.6	TABULA standard value
F_F	0.3	TABULA standard value
F_W	0.9	TABULA standard value
$F_{nu,A}$ ($h_{tr} \leq h_A$)	0.95	TABULA standard value for multi-unit housing
F_{nu} ($h_A < h_{tr} < h_B$)	$F_{nu,A}+(F_{nu,B}-F_{nu,A})\cdot\dfrac{h_{tr}-h_A}{h_B-h_A}$	TABULA equation
$F_{nu,B}$ ($h_{tr} \geq h_B$)	0.85	TABULA standard value for multi-unit housing

Abbreviation	Value	Source
h_A	1	TABULA standard value
h_{tr}	$\frac{H_{tr}}{A_{C,ref}}$	TABULA equation
h_B	4	TABULA standard value
$h_{room,ve,ref}$	2.5	TABULA standard value
H_{ve}	$c_{p,air} \cdot (n_{air,use} + n_{air,infiltr}) \cdot A_{C,ref} \cdot h_{room,ve,ref}$	TABULA equation
H_{tr}	$(b_{tr,ext} \cdot A_{env,wall} \cdot U_{eff,wall} + b_{tr,ext} \cdot A_{env,window} \cdot U_{eff,window} + b_{tr,soil} \cdot A_{env,floor} \cdot U_{eff,floor} + b_{tr,ext} \cdot A_{env,door} \cdot U_{eff,door} + b_{tr,ext} \cdot A_{env,roof} \cdot U_{eff,roof}) + (A_{env.wall} + A_{env,window} + A_{env,floor} + A_{env,door} + A_{env,roof}) \cdot dU_{thr}$	TABULA equation
$I_{sol,hor}$	336	Calculated, source: NS3031, tab. M2
$I_{sol,east}$	240	Calculated, source: NS3031, tab. M2
$I_{sol,west}$	240	Calculated, source: NS3031, tab. M2
$I_{sol,north}$	114	Calculated, source: NS3031, tab. M2
$I_{sol,south}$	413	Calculated, source: NS3031, tab. M2
ϕ_{int}	5.25	NS 3031: Table A2
ϑ_{int}	22	Value for apartments constructed between 1991-2010, Mjønes et al., 2012, p. 44
ϑ_e	3.4	Calculated from Enøk normtall, p. 63
$q_{g,w,h}$	0	Assuming no loss
$q_{s,h}$	0	Assuming no loss
$q_{d,h}$	0	Assuming no loss
$q_{nd,w}$	29.8	Tab. A1, NS 3031
$R_{measure,wall}$	0	Default, no refurbishment
$R_{measure,window}$	0	Default, no refurbishment
$R_{measure,floor}$	0	Default, no refurbishment
$R_{measure,door}$	0	Default, no refurbishment
$R_{measure,roof}$	0	Default, no refurbishment
$R_{add,wall}$	0	Assuming disconnected building
$R_{add,window}$	0	Assuming disconnected building
$R_{add,floor}$	0	Assuming disconnected building
$R_{add,door}$	0	Assuming disconnected building
$R_{add,roof}$	0	Assuming disconnected building
$R_{eff,wall}$	$R_{0,wall} + R_{measure,wall} + R_{add,wall}$	TABULA equation
$R_{eff,window}$	$R_{0,window} + R_{measure,window} + R_{add,window}$	TABULA equation
$R_{eff,floor}$	$R_{0,floor} + R_{measure,floor} + R_{add,floor}$	TABULA equation
$R_{eff,door}$	$R_{0,door} + R_{measure,door} + R_{add,door}$	TABULA equation

Abbreviation	Value	Source
$R_{eff,roof}$	$R_{0,roof} + R_{measure,roof} + R_{add,roof}$	TABULA equation
$t_{døgn}$	0.024	Standard value
τ	$\dfrac{c_m \cdot A_{ref}}{H_{tr} + H_{ve}}$	TABULA standard value
$\tau_{H,0}$	30	TABULA standard value
$U_{eff,wall}$	1/R_eff.wall	Standard equation
$U_{eff,window}$	1/R_eff.window	Standard equation
$U_{eff,floor}$	1/R_eff.floor	Standard equation
$U_{eff,door}$	1/R_eff.door	Standard equation
$U_{eff,roof}$	1/R_eff.roof	Standard equation

A.3 Energy balance equations

$$Q_{H,nd} = Q_{ht,ve} + Q_{ht,tr} - n_{h,gn} \cdot (Q_{sol} + Q_{int}) \tag{11}$$

$$Q_{g,h} = Q_{del,h} + n_{h,gn} \cdot (Q_{ve,h,rec} + Q_{w,h}) - Q_{H,nd} - Q_{s,h} - Q_{d,h} \tag{12}$$

$$Q_{g,w} = Q_{del,w} - Q_{n,dw} - Q_{s,w} - Q_{d,w} \tag{13}$$

$$\eta_{h,gn} = \frac{1 - y^{a_H}}{1 - y^{a_H + 1}} \tag{14}$$

$$\begin{aligned} Q_{sol} = F_{sh} \cdot (1 - F_F) \cdot F_W \cdot g_{gl,n} \cdot (&A_{window,hor} \cdot I_{sol,hor} + A_{window,east} \cdot I_{sol,east} \\ &+ A_{window,west} \cdot I_{sol,west} + A_{window,north} \cdot I_{sol,north} + A_{window,south} \cdot I_{sol,south}) \end{aligned} \tag{15}$$

$$Q_{int} = 0.024 \cdot \varphi_{int} \cdot d_{hs} \cdot A_{C,ref} \tag{16}$$

$$Q_{ht,ve} = 0.024 \cdot H_{ve} \cdot F_{nu} \cdot (u_{int} - u_e) \cdot d_{hs} \tag{17}$$

$$Q_{ht,tr} = 0.024 \cdot H_{tr} \cdot F_{nu} \cdot (u_{int} - u_e) \cdot d_{hs} \tag{18}$$

$$Q_{del,h,1} = a_{nd,h,1} \cdot e_{g,h,1} \cdot (Q_{H,nd} - n_{h,gn} \cdot (Q_{w,h} + Q_{ve,h,rec}) + Q_{d,h} + Q_{s,h}) \tag{19}$$

$$Q_{del,h,2} = a_{nd,h,2} \cdot e_{g,h,2} \cdot (Q_{H,nd} - n_{h,gn} \cdot (Q_{w,h} + Q_{ve,h,rec}) + Q_{d,h} + Q_{s,h}) \tag{20}$$

$$Q_{del,h,3} = a_{nd,h,1} \cdot e_{g,h,3} \cdot (Q_{H,nd} - n_{h,gn} \cdot (Q_{w,h} + Q_{ve,h,rec}) + Q_{d,h} + Q_{s,h}) \tag{21}$$

$$Q_{del,h} = Q_{del,h,1} + Q_{del,h,2} + Q_{del,h,3} \tag{22}$$

$$Q_{ve,h,rec} = n_{ve,rec} \cdot Q_{ht,ve} \tag{23}$$

$$Q_{w,h} = (q_{g,w,h} + q_{s,w,h} + q_{d,w,h}) \cdot A_{C,ref} \tag{24}$$

$$Q_{s,h} = q_{s,h} \cdot A_{C,ref} \tag{25}$$

$$Q_{d,h} = q_{d,h} \cdot A_{C,ref} \tag{26}$$

$$Q_{del,w,1} = a_{nd,w,1} \cdot e_{g,w,1} \cdot (Q_{nd,w} + Q_{d,w} + Q_{s,w}) \tag{27}$$

$$Q_{del,w,2} = a_{nd,w,2} \cdot e_{g,w,2} \cdot (Q_{nd,w} + Q_{d,w} + Q_{s,w}) \tag{28}$$

$$Q_{del,w,3} = a_{nd,w,3} \cdot e_{g,w,3} \cdot (Q_{nd,w} + Q_{d,w} + Q_{s,w}) \tag{29}$$

$$Q_{del,w} = Q_{del,w,1} + Q_{del,w,2} + Q_{del,w,3} \tag{30}$$

$$Q_{nd,w} = q_{nd,w} \cdot A_{C,ref} \tag{31}$$

$$Q_{s,w} = q_{s,w} \cdot A_{C,ref} \tag{32}$$

$$Q_{d,w} = q_{d,w} \cdot A_{C,ref} \tag{33}$$

B Cost calculation details

B.1 Simplifications for the cost analysis

The final costs include most costs related to building envelope and heating system, but excludes some costs that will be similar for all rehabilitations, such as maintenance of the building envelope (except for the replacement of wall cladding), purchase and maintenance of DHW tank and its piping systems. Costs for cooling are not included, as this is not an output of the energy balance model.

Resale values for retrofit insulation have been omitted, as life times for insulation has not been found. Retrofit insulation is added fairly early in all cases and it is therefore assumed that the resale value is fairly low.

At the moment, PV panels installed on top of a typical office building in Oslo will have a levelised energyu cost of about 2 NOK/kWh (Multiconsult 2013). This is currently not a competitive price compared to electricity from the grid, and is therefore not evaluated in this project.

Solar collectors need some energy for running pumps. These energy inputs have not been evaluated.

Gas-based technologies and wood chippings as fuels are omitted, as the information was scarce, and because they did not appear to be significantly relevant based on the literature study. The solar collectors are based on the available information from Kveim (2013). Enova provides financial support for solar collectors based on their maximum power delivery. As the maximum power is not provided for the chosen system, the support cannot be calculated, and is therefore excluded.

Efficiencies include losses from production, regulation, and transfer when applicable. Efficiencies can be slightly lower for heating systems older than 1990, according to NS 3031. This has not been considered, in order to simplify the calculations.

Some municipals, including Oslo, offer support arrangements for energy rehabilitations. These are not included in the LCC calculations.

Firewood prices were evaluated, but not used as a rehabilitation alternative. The prices vary to a large degree, depending on location, time of year, and bulk size. The price here is based on buying 1 m^3 of wood, as this might be realistic if the apartments have room for storage in the basement or attic.

Oil boiler costs include an electric boiler, which has been omitted in the other cases. This means that the costs for a DHW boiler and electric radiators probably should be subtracted for the 1O case. However, as oil boiler is not a viable option (and thus not as interesting for price comparison with other cases), and DHW prices are chosen to be excluded from the calculations, this has not been looked further into.

Predicted development in future costs and technology are not evaluated. Only one climatic zone has been considered. Other technologies for heating, ventilation, and insulation exist, but the spreadsheet includes those assumed to be the most relevant only.

The ventilation systems are based on constant air volume, as this is the normal solution for apartment buildings. Automation and detectors have not been evaluated, as these measures are based on regulation or user behaviour, and therefore not relevant for the project scope. Individual gas stoves have been omitted, as this technology did not seem to be very common.Costs have been included for the energy carriers gas and bio-gas, but as they were highly uncertain, they will not be used in any calculations. Oil boilers can be converted into boilers able to run on bio-oil. However, the price of both types of oil are very high compared to other energy carriers, and this is therefore not expected to be a profitable option as part of a renovation package.

B.2 Input values

The following tables contain all input values used for cost calculations, as well as their sources.

Table 35: Acquisition and installation costs for heating sources

Heating source, air heating	Acquisition cost (incl. Installation)	
Electricity, direct	176.25	[NOK/m2] Holte Kalkulasjonsnøkkelen 2013, 32. utgave, red: Per Kveim, p. 93, 25 % MVA added
Electricity, boiler	0	Included in combination alternatives
Heat pump (air-air) 3 kW	25401.75	[NOK/stk] Norsk Prisbok 2013, p. D-203
Heat pump (ground-water) 30 kW	413549.13	[NOK] Norsk Prisbok 2013, p. D-203
Heat pump (ground-water) 60 kW	565755.63	[NOK] Norsk Prisbok 2013, p. D-203
District heating 50 kW	114611	[NOK] Bioen AS, 2010, 'Kostnader for fjernvarmeutbygging', p. 5, adjusted for inflation
District heating 100 kW	130240	[NOK] Bioen AS, 2010, 'Kostnader for fjernvarmeutbygging', p. 5, adjusted for inflation
Oil (boiler)	-	-
Bio-oil (boiler)	563	[NOK/m2] Oil + el, Holte Kalkulasjonsnøkkelen 2013, p. 92
Gas (boiler)	563	[NOK/m2] incl. el. boiler Assuming same as for oil boiler
Bio-gas (boiler)	563	[NOK/m2] incl. el. boiler Assuming same as for oil boiler
Wood pellets (boiler) 38 kW	214100	[NOK]For Fröling P4, extra equipment and installation. Source: Brennum, C. 14.05.2014, SGP Varmeteknikk AS, Personal communication
Wood pellets (boiler) 48 kW	231800	[NOK]For Fröling P4, extra equipment and installation. Source: Brennum, C. 14.05.2014, SGP Varmeteknikk AS, Personal communication
Wood pellets (boiler) 55 kW	272271	[NOK] Calculation based on linear extrapolation of prices for the other two boilers.
Firewood (stove) 4 kW	6875	[NOK] Dovre 100 CB. Ordinary price, one stove, Source: http://www.henriksen-brensel.no/vedovner/dovre-100-cb-dovre-372#!prettyPhoto [Accessed 11. May 2014]
Firewood (boiler) 35 kW	214100	[NOK] Assuming same as pellets
Solar heater, 6548 kWh/year	138762.75	[NOK] Norsk Prisbok 2013, p. D-202

Table 36: Energy costs for 1 kWh delivered to heating system

Heating source, air heating	Energy costs, input	
Electricity	0.596	[NOK/kWh]Average costs 2013, Calculated from electricity prices (http://www.ssb.no/energi-og-industri/statistikker/elkraftpris/kvartal/2014-02-25#content) and grid rental (https://www.lysenett.no/getfile.php/Prishefte %20nettleie%202013%20%2802%29.pdf)
District heating	0.713	[NOK/kWh]Average price 2012, adjusted for inflation to 2013-price
Oil (boiler)	1.045	[NOK/kWh]Average costs 2013 http://www.np.no/priser/, incl. New taxes as of 2014 (http://www.novap.no/artikler/prishopp-pa-fyringsolje-og-parafin-fra-nyttaar) based on 10 kWh/liter (http://oljefri.no/bolig/oekonomi/category1163.html), accessed 09.05.14
Bio-oil	0.912	[NOK/kWh] http://www.energi1olje.no/, accessed 09.05.14, assuming same energy density as regular fuel oil
Gas	0.74	[NOK/kWh]Costs in 2020, in 2013-NOK, calculated from Lindberg & Magnussen (2010, pp. 54-55) based on 9.02 % price increase since 2008 (Norges Bank)
Bio-gas	0.43	[NOK/kWh]Costs in 2014, in 2013-NOK, calculated from Lindberg & Magnussen (2010, pp. 54-55) based on 9.02 % price increase since 2008 (Norges Bank)
Wood pellets 38 kW	0.72	[NOK/kWh] Enova, average http://www.enova.no/radgivning/privat/rad-om-produkter-og-losninger/oppvarmingsalternativ/ pelletskamin/pelletskamin-/114/136/
Firewood	0.66	[NOK/kWh]Calculated based on prices for birch wood in 1000 l bag (949 kr in 2013) from Østfold ved (http://www.ostfoldved.no/index.php?option=com_content &view=article&id=45&Itemid=53) and energy content 1.435 kWh/l from Enova (http://www.enova.no/radgivning/privat/rad-om-produkter-og-losninger/oppvarmingsalternativ/vedovn/ vedovn/118/140/) [Accessed 11 May 2014]

Table 37: Energy system efficiencies

Heating source	Efficiency [%]		Energy cost, output to building	
Electricity, direct	98 %	NS 3031, Table B.9	0.608	[NOK/kWh]
Electricity, boiler	88 %	NS 3031, Table B.9	0.674	[NOK/kWh]
Heat pump (air-air) 3 kW	216 %	NS 3031, Table B.9	0.276	[NOK/kWh]
Heat pump (ground-water)	222 %	NS 3031, Table B.9	0.268	[NOK/kWh]
District heating	88 %	NS 3031, Table B.8	0.810	[NOK/kWh]
Oil (boiler)	77 %	NS 3031, Table B.9	1.357	[NOK/kWh]
Bio-oil (boiler)	77 %	NS 3031, Table B.9	1.184	[NOK/kWh]
Gas (boiler)	81 %	NS 3031, Table B.9	0.914	[NOK/kWh]
Bio-gas (boiler)	81 %	NS 3031, Table B.9	0.531	[NOK/kWh]
Wood pellets (boiler)	77 %	NS 3031, Table B.9	0.935	[NOK/kWh]
Firewood (stove) 4 kW	64 %	NS 3031, Table B.9	1.031	[NOK/kWh]
Firewood (boiler) 35 kW	77 %	NS 3031, Table B.9	0.857	[NOK/kWh]

Table 38: Maintenance costs for energy systems

Heating source	Maintenance costs	
Electricity, direct	0	Assumption
Electricity, boiler	0.055	[NOK/kWh]Costs in 2020, in 2013-NOK, calculated from Lindberg & Magnussen (2010, pp. 54-55) based on 9.02 % price increase since 2008 (Norges Bank)
Heat pump (air-air) 3 kW	953	[NOK/year] http://www.statsbygg.no/FilSystem/files/Dokumenter/veiledninger/Varmepumpeveileder/varmepumpe.htm#55, part 5.5, average value
Heat pump (ground-water) 30 kW	15508	[NOK/year] http://www.statsbygg.no/FilSystem/files/Dokumenter/veiledninger/Varmepumpeveileder/varmepumpe.htm#55, part 5.5, average value
Heat pump (ground-water) 60 kW	21216	[NOK/year] http://www.statsbygg.no/FilSystem/files/Dokumenter/veiledninger/Varmepumpeveileder/varmepumpe.htm#55, part 5.5, average value
District heating 50 kW	3438	[NOK/m2*year] Lunden, R., Personal communication 9. Nov. 2012, Statkraft Varme AS
District heating 100 kW	3907	[NOK/m2*year] Lunden, R., Personal communication 9. Nov. 2012, Statkraft Varme AS
Oil (boiler)	0.055	[NOK/kWh]Costs in 2020, in 2013-NOK, calculated from Lindberg & Magnussen (2010, pp. 54-55) based on 9.02 % price increase since 2008 (Norges Bank)
Bio-oil (boiler)	0.055	[NOK/kWh] Assuming same as for fuel oil boiler
Gas / bio-gas(boiler)	0.055	[NOK/kWh]Costs in 2020, in 2013-NOK, calculated from Lindberg & Magnussen (2010, pp. 54-55) based on 9.02 % price increase since 2008 (Norges Bank)
Wood pellets (boiler)	1750	[NOK/year] Brennum, C. 14.05.2014, SGP Varmeteknikk AS, Personal communication. Assuming 150 NOK for travel/food
Firewood (stove) 4 kW	1000	[NOK/year] Calculated from prices in Oslo, http://www.brann-og-redningsetaten.oslo.kommune.no/getfile.php/brann-%20og%20redningsetaten%20%28BRE%29/Internett%20%28BRE%29/Bilder/Forebyggende/Priser%20med%20beskrivelse%202014%20gebyr%20til%20nettsidene.pdf & http://www.brann-og-redningsetaten.oslo.kommune.no/getfile.php/brann-%20og%20redningsetaten%20%28BRE%29/Internett%20%28BRE%29/Dokumenter/Brannvern%20i%20bolig/Brev%20rundt%20feie%20og%20tilsynsgebyr%202013.pdf

Heating source	Maintenance costs	
Firewood (boiler) 35 kW	0.055	[NOK/kWh]Costs in 2020, in 2013-NOK, calculated from Lindberg & Magnussen (2010, pp. 54-55) based on 9.02 % price increase since 2008 (Norges Bank)
Solar heater	2000	[NOK] Assumption basd on 4000 NOK for heater 5 times the size. http://prezi.com/ruvcailsjqg4/solfangere-til-nringsbygg-pa-vestlandet/

Table 39: Technical lifetimes of energy systems

Heating source	Lifetime	
Electricity, direct	25	[years] p. A-9, Norsk prisbok 2012
Electricity, boiler	20	[years] Skanska, Vedlikeholdsplan Rykkin skole, provided by Boland, Leif Sverre on e-mail 25. March 2014
Heat pump (air-air) 3 kW	23	[years] http://www.statsbygg.no/FilSystem/files/Dokumenter/veiledninger/Varmepumpeveileder/-varmepumpe.htm#55, part 13.2.1, average value
Heat pump (ground-water)	23	[years] http://www.statsbygg.no/FilSystem/files/Dokumenter/veiledninger/Varmepumpeveileder/-varmepumpe.htm#55, part 13.2.1, average value
District heating	25	[years] Based on information from various suppliers: http://www.nilan.dk/da-dk/forside/loesninger/erhvervsloesninger/faq.aspx #hvor-langlevetid & http://dk.private.danfoss.com/Content/3DD844EB-030B-4740-8C7E-8F6F817D8F96_MNU17494484_SIT96.html
Oil (boiler)	20	[years] Assuming same as other boilers
Bio-oil (boiler)	20	[years] Assuming same as other boilers
Gas (boiler)	20	[years] Assuming same as other boilers
Bio-gas (boiler)	20	[years] Assuming same as other boilers
Wood pellets (boiler)	20	[years] For Fröling P1, Brennum, C. 15.04.2014, SGP Varmeteknikk AS, Personal communication
Firewood (stove) 4 kW	30	[years] p. A-9, Norsk prisbok 2012
Firewood (boiler) 35 kW	20	[years] Assuming same as other boilers
Solar heater	30	[years] http://www.husogheim.no/1/1_40.html, Accessed 25. Apr. 2014

Table 40: Expected financial support from Enova for installations of various heating systems, sorted by building standard qualifications

Heating source	Passive house	TEK 10	
Heat pump (air-air) 3 kW · 24	79 200	-	[NOK] Enova n.d.-b
Heat pump (ground-water) 30 kW	48 000	15 000	[NOK] Enova n.d.-b
Heat pump (ground-water) 60 kW	96 000	30 000	[NOK] Enova n.d.-b
Wood pellets (boiler) 38 kW	64 600	22 800	[NOK] Enova n.d.-b
Wood pellets (boiler) 48 kW	81 600	28 800	[NOK] Enova n.d.-b
Wood pellets (boiler) 55 kW	93 500	33 000	[NOK] Enova n.d.-b
Solar heater	201	201	[NOK/kWh]Enova n.d.-b

Table 41: Acquisition and installation costs for ventilation and hydronic heating

System upgrades	Acquisition cost (incl. Installation)		Efficiency [%]	
Hydronic heating	810.5	[NOK/m2] Norsk Prisbok 2013, p. D-200, 25 % MVA added		
Mechanical ventilation, upgrade after 15 years	59.17	[NOK/m2]Assuming same rate as for http://biblioteket.husbanken.no/arkiv/dok/Komp /Nordre%20Gran/Rapport.pdf, p. 25	0	Definition
Balanced ventilation, upgrade after 15 years	80	[NOK/m2]Assuming slightly higher than for mechanical ventilation, because of heat recovery unit and longer ducts	0.8	TEK 10 requirement
Replacement of mechanical ventilation to balanced	355	[NOK/m2]Calc. From Holte p. 92, 25 % MVA added. Assuming rotating heat recovery unit without heating coil. This type can provide an efficiency of 80-84 %, unless the climate is very low. (Lavenergiprogrammet 2009), accessed 2. May 2014, http://www.google.no/url ?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad =rja&uact=8&ved=0CCkQFjAA&url=http%3A %2F%2Fwww.lavenergiprogrammet.no%2Fgetfile. php%2FRapporter%2520og%2520veiledninger%2F0 7%2520Boligventilasjon%2520090612.pptx&ei=RLB jU8_zAaWqyAOC3IDYDQ&usg=AFQjCNH0sTn3 xUnuQpkqOVPGqrdWx-toIHA&bvm=bv.65788261,d.bGQ	0.8	TEK 10 requirement

Table 42: Maintenance costs for ventilation and hydronic heating

System upgrades	Maintenance costs		Lifetime	
Hydronic heating	0	Assumption. Should be very low (source: http://www.purmo.com/docs/Purmo_LTR_NO_LOW.pdf, p. 15) and within lifetime, work is probably only done to pumps, if any at all.	40	[years] p. A-9, Norsk prisbok 2012, average
Mechanical ventilation, upgrade after 15 years	150	[NOK/year] Must be lower than for balanced ventilation. ”Minimal, but cleaning is required, and condensators might have to be replaced”, according to Hans Einar Sætra, e-mail to Ragni Storvolleng, 2. May 2014.	15	[years] Assuming same as balanced
Balanced ventilation, upgrade after 15 years	237	[NOK /year] http://www.sintef.no/upload/Teknologi_og_samfunn/Arkitektur%20og%20byggteknikk/Lavenergiboliger/HusbyRehab-TeknRapport.pdf, p. 8, adjusted for inflation	15	[years] http://www.sintef.no/upload /Teknologi_og_samfunn/Arkitektur%20og%20byggteknikk/Lavenergiboliger/Husby Rehab-TeknRa pport. pdf, p. 7
Replacement of mechanical ventilation to balanced	237	[NOK /year] http://www.sintef.no/upload/Teknologi_og_samfunn/Arkitektur%20og%20byggteknikk/Lavenergiboliger/HusbyRehab-TeknRapport.pdf, p. 8, adjusted for inflation	15	[years] http://www.sintef.no/upload/Teknologi_og_samfunn/Arkitektur%20og%20byggteknikk/Lavenergiboliger/Husby Rehab-TeknRapport.pdf, p. 8

Table 43: Acquisition and installation costs for building envelope components

Building envelope upgrades	Acquisition cost (incl. Installation)	
New windows + doors U-value ¡ 1.6	4023.25	[NOK/m2 windows and door]Norsk prisbok D-068
New windows + doors U-value ¡ 1.2	4370.875	[NOK/m2 windows and door]Norsk prisbok D-068
New windows + doors U-value = 0.7	5077.75	[NOK/m2 windows and door]Norsk prisbok D-068
Insulation, walls, 81-00 TEK 10 [kr/m2]	28.14	[NOK/m2 wall] Additional insulation, calculated from B-plate, http://www.rockwool.no/priser/bygg, approximately 335 kr/m thickness
Insulation, walls, 81-00 Passive [kr/m2]	266.995	[NOK/m2 wall] Calculated as above
Insulation, walls, 01-10 TEK 10 [kr/m2]	24.79	[NOK/m2 wall] Calculated as above
Insulation, walls, 01-10 Passive [kr/m2]	72.025	[NOK/m2 wall] Calculated as above
Insulation, ceiling and roof, 81-00 TEK 10 [kr/m2]	58.625	[NOK/m2] Calculated as above
Insulation, ceiling and roof, 81-00 Passive [kr/m2]	191.285	[NOK/m2] Calculated as above
Insulation, ceiling and roof, 01-10 TEK 10 [kr/m2]	7.37	[NOK/m2] Calculated as above
Insulation, ceiling and roof, 01-10 Passive [kr/m2]	133.665	[NOK/m2] Calculated as above
Walls, cladding, including demolition	1171.875	[NOK/m2 wall] Holte Kalkulasjonsnøkkelen 2013, p.91, 25 % MVA added

Lifetime of windows: 25 years, lifetime of cladding: 40 years. (Source: Norsk prisbok 2012, p. A-9)

B.3 NPV example

The following table contains an example NPV calculation. All calculations can be found in the Excel cost model in App. D. The table has been split into six parts in order to make it fit the page format.

Table 44: Calculation example, NPV of case 1ED, TEK 10. Based on present costs.

Year	2014	2015	2016	2017
Time from 2014	-	1.00	2.00	3.00
Acquisition and installation costs	4 715 211.86	-	-	-
Energy cost	63 087.38	63 087.38	63 087.38	63 087.38
Maintenance	7 585.18	7 585.18	7 585.18	7 585.18
Support / resale value	-	-	-	-
Discount rate	0.05			
NPV	4 785 884.41	67 307.19	64 102.09	61 049.61

2018	2019	2020	2021	2022	2023	2024
4.00	5.00	6.00	7.00	8.00	9.00	10.00
-	-	-	-	-	-	-
63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38
7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18
-	-	-	-	-	-	-
58 142.48	55 373.80	52 736.95	50 225.66	47 833.97	45 556.16	43 386.82

2025	2026	2027	2028	2029	2030	2031
11.00	12.00	13.00	14.00	15.00	16.00	17.00
-	-	-	-	145 920.00	-	-
63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38
7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18
-	-	-	-	-	-	-
41320.77844	39 353.12	37 479.16	35 694.44	104 184.72	32 375.91	30 834.20

2032	2033	2034	2035	2036	2037	2038
18.00	19.00	20.00	21.00	22.00	23.00	24.00
-	-	-	-	-	-	-
63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38
7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18
-	-	-	-	-	-	-
29 365.91	27 967.53	26 635.74	25 367.37	24 159.40	23 008.96	21 913.29

2039	2040	2041	2042	2043	2044	2045
25.00	26.00	27.00	28.00	29.00	30.00	31.00
1 326 111.40	-	-	-	-	145 920.00	-
63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	63 087.38
7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	7 585.18
-	-	-	-	-	-	-
412 474.17	19 876.00	18 929.52	18 028.12	17 169.64	50 114.63	15 573.37

2046	2047	2048	2049	2050	Total
32.00	33.00	34.00	35.00	36.00	
-	-	-	-	-	1 617 951.40
63 087.38	63 087.38	63 087.38	63 087.38	63 087.38	2 271 145.60
7 585.18	7 585.18	7 585.18	7 585.18	7 585.18	273 066.34
-	-	-	-	999 028.33	999 028.33
					0.05
14 831.78	14 125.50	13 452.86	12 812.25	-160 287.51	6 278 360.01

B.4 NPV results

Table 45: NPV for various rehabilitation combinations [NOK] for buildings constructed between 1981-1990, based on present price level

Base cases	Original state	W/D TEK 10	W/D Passive	TEK 10	Passive
1E	4 437 117	4 426 398	4 510 142	4 889 747	5 153 670
1ED	6 102 737	6 050 478	6 044 974	6 278 360	6 423 825
1EHa	4 737 032	4 787 956	4 945 158	5 600 732	5 921 074
1EP	6 478 298				
1EHg	6 069 883				
1Es	4 528 086				
1O	7 922 421				
1OHg	5 707 179				
1OHa	5 058 512				

Table 46: NPV for various rehabilitation combinations [NOK] for buildings constructed between 1981-1990, based on doubling of electricity price

Base cases	Original state	W/D TEK 10	W/D Passive	TEK 10	Passive
1E	6 288 788	6 152 691	6 087 031	5 905 343	5 893 431
1ED	6 842 498	6 790 238	6 784 735	7 018 121	7 163 586
1EHa	6 042 014	6 029 205	6 110 459	6 480 709	6 660 835
1EP	7 329 249				
1EHg	7 362 593				
1Es	6 302 331				
1O	8 773 372				
1OHg	6 999 889				
1OHa	6 363 494				

Table 47: NPV for various rehabilitation combinations [NOK] for buildings constructed between 1991-2000, based on present price level

Base cases	Original state	W/D TEK 10	W/D Passive	TEK 10	Passive
2E	3 570 767	3 605 614	3 684 808	4 092 438	4 400 504
2ED	5 063 472	4 864 792	4 898 831	5 348 978	5 531 665
2EHa	4 275 669	4 348 117	4 494 318	4 792 253	5 048 565
2EP	6 323 247				
2EHg	5 480 459				
2Es	3 674 617				

Table 48: NPV for various rehabilitation combinations [NOK] for buildings constructed between 1991-2000, based on doubling of electricity price

Base cases	Original state	W/D TEK 10	W/D Passive	TEK 10	Passive
2E	5 140 890	5 104 618	5 047 524	4 949 760	5 072 129
2ED	5 735 096	5 536 417	5 570 456	6 020 603	6 175 882
2EHa	5 404 031	5 440 325	5 517 247	5 916 454	6 078 370
2EP	7 762 556				
2EHg	6 598 904				
2Es	5 167 316				

Table 49: NPV for various rehabilitation combinations [NOK] for buildings constructed between 2001-2010, based on present price level

Base cases	Original state	W/D TEK 10	W/D Passive	TEK 10	Passive
3E	1 766 402	2 527 539	2 605 729	3 055 497	3 305 781
3EHa	2 630 774	3 287 806			
3EP	3 698 263				
3EHg	3 874 852				
3Es	1 880 881				
3D	2 071 498	2 795 421	2 827 352	3 229 148	3 403 454
3P	2 260 234	3 013 781	3 006 196	3 326 741	3 488 604

Table 50: NPV for various rehabilitation combinations [NOK] for buildings constructed between 2001-2010, based on doubling of electricity price

Base cases	Original state	W/D TEK 10	W/D Passive	TEK 10	Passive
3E	2 628 890	3 277 705	3 216 275	3 521 250	3 588 761
3EHa	3 208 337	3 782 750			
3ED	3 692 815				
3EP	4 019 983				
3EHg	4 446 019				
3Es	2 711 665				
3D	2 354 478	3 078 400	3 110 332	3 512 127	3 686 434
3P	2 601 165	3 343 480	3 321 932	3 627 998	3 771 584

C Scenario model details

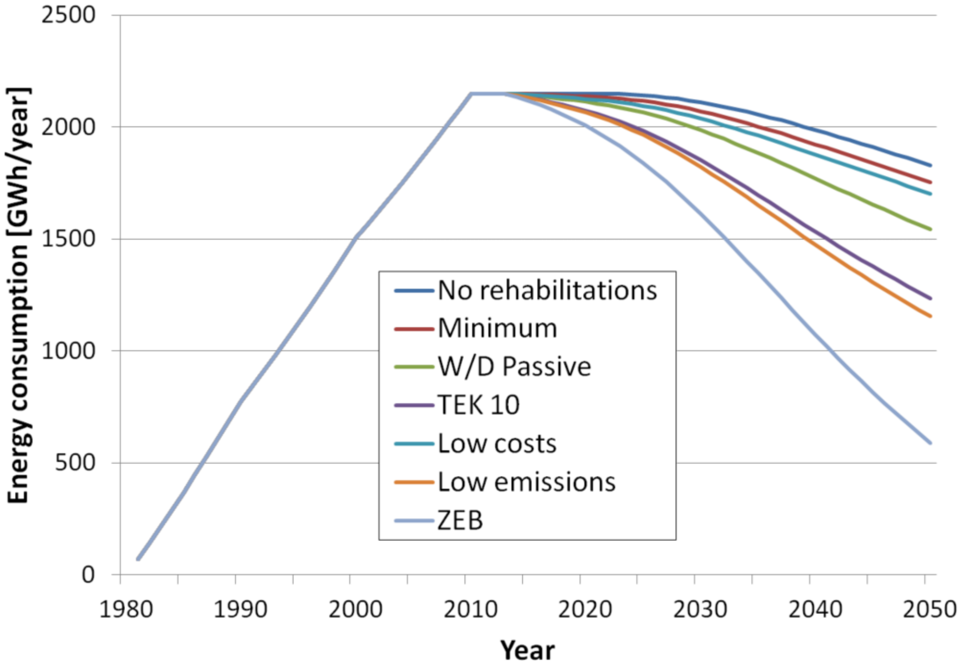

Figure 36: Simulated total energy consumption for heating in Norwegian apartment blocks, sorted by energy scenarios, for the years 1980-2050.

Table 51: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks in 2050, sorted by energy scenarios, compared to the simulated emissions in 2014. Emissions from electricity based on Norwegian mix.

Scenario	Emissions [kton CO_2]	Share of emissions in 2014
2014 level	132	100 %
No rehab.	113	85 %
Minimum	108	82 %
W/D Passive	88	66 %
TEK 10	71	54 %
Low costs	98	74 %
Low emissions	65	49 %
ZEB	37	28 %

Table 52: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks in 2050, sorted by energy scenarios, compared to the simulated emissions in 2014. Emissions from electricity based on Red emission scenario.

Scenario	Emissions [kton CO_2]	Share of emissions in 2014
2014 level	733	100 %
No rehab.	473	64 %
Minimum	453	62 %
W/D Passive	399	54 %
TEK 10	319	44 %
Low costs	440	60 %
Low emissions	298	41 %
ZEB	152	21 %

Table 53: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks in 2050, sorted by electricity mix definition, compared to the simulated emissions in 2014. Energy consumption based on Low costs scenario.

	Emissions [kton CO_2]		
Year	2014	2040	Share of emissions in 2014
Norwegian	132	98	74 %
Nordic	437	345	79 %
EU27	1 131	908	80 %
Red	732	440	60 %
Yellow	711	332	47 %
Green	707	274	39 %
Ultra Green	696	67	10 %
Blue	691	203	29 %

Table 54: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks in 2050, sorted by electricity mix definition, compared to the simulated emissions in 2014. Energy consumption based on Low emissions scenario.

	Emissions [kton CO_2]		
Year	2014	2040	Share of emissions in 2014
Norwegian	132	65	50 %
Nordic	435	233	54 %
EU27	1 128	617	55 %
Red	730	298	41 %
Yellow	709	224	32 %
Green	705	185	26 %
Ultra Green	694	44	6 %
Blue	689	137	20 %

Table 55: Simulated CO_2 emissions from energy use for heating in Norwegian apartment blocks in 2050, sorted by electricity mix definition, compared to the simulated emissions in 2014. Energy consumption based on TEK 10 scenario.

	Emissions [kton CO_2]		
Year	2014	2040	Share of emissions in 2014
Norwegian	132	71	54 %
Nordic	435	250	57 %
EU27	1 128	658	58 %
Red	730	319	44 %
Yellow	710	241	34 %
Green	706	199	28 %
Ultra Green	695	48	7 %
Blue	689	147	21 %

D CD with electronic documents

This CD contains all calculation models and results for the energy balance, costs, future energy consumption, and future emissions. Results from the building stock model are not included, as it is part of a different research project, and not to be redistributed. Directions for using the models are provided in the first spreadsheet in all documents.