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 Marie Folstad

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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

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 cost and energy-related greenhouse gas emissions.

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

Olav Bolland
Department Head

Helge Brattebø
Academic Supervisor

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Preface

The objective of this Master Thesis is to carry out a system analysis of a defined part of the Norwegian building stock in order to better understand trends in future annual energy demand. The work is connected to the EU's Intelligent Energy Europe funded EPISCOPE project, a follow-up of the recent TABULA project.

Since the Norwegian building stock is very complex and consists of many different building typologies it was decided to include four students on this project. It was decided that two students should look at apartment blocks built before and after 1980 and two students should look at detached houses built before and after 1980. This report focuses on apartment blocks built before 1980. The project team has collaborated throughout the semester when it comes to literature study and I would therefore like to thank Ragni Storvolleng, Anja Myreng Skaran and Marta Baltruszewicz for a good working relationship.

I would also like to give a special thanks to my supervisor, Helge Brattebø, and co supervisor Nina Sandberg, who has followed up in great detail and supported me with relevant literature.

Marie Folstad

Trondheim, Norway
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Abstract

Three building typologies are analyzed in this report, where the first one is apartment blocks built before 1956, the second one is apartment blocks built in the period 1956-1970, and the last typology is apartment blocks built in the period 1971-1980. A literature study of typical dwellings throughout time is completed and typical apartments from each of the time periods are defined.

The model used to calculate the building's energy need for space heating and domestic hot water is based on the TABULA methodology, but is constructed as an energy balance model that uses the principles of a material flow analysis. This model is used to calculate the energy need before and after renovation. For each time period two building states are analyzed; original building state and historical refurbished building state. This is done since a big part of the buildings built before 1980 have already gone through some sort of renovation, and the energy saving potential by implementing new energy efficiency measures to these partly refurbished buildings are smaller than the energy saving potential for the same building types in original state. A life cycle costing model that uses the principles of net present value is used to calculate the economical output of each renovation package analyzed in this Master Thesis. A scenario model, that uses inputs from the segmented building stock model (see chapter 3.3.1) and the energy model (see chapter 3.1), is used to estimate the future energy need for space heating and domestic hot water for the part of the Norwegian dwelling stock analyzed in this report.

The energy reduction potential for improving a typical building constructed before 1956 from original state to TEK10 level is 68 % for space heating. Improving it further down to a passive house level gives a reduction potential of 81 %, which shows that these buildings have a major improvement potential. Only a minority (16%) of the apartment blocks from this period are however in original state, which means that a more realistic reduction potential is seen from historical refurbished state to TEK10- or passive house level. The reduction potential for a TEK10-refurbishment is then 46 % and 67 % for a passive house refurbishment. For the two other building typologies the general pattern is that the energy savings decrease as the quality of the building in original and historical refurbished state improves. Apartment blocks built between 1971 and 1980 have the lowest saving potential since the quality before new renovation is high. This also makes these building types less economical efficient for different renovation projects. General it is shown that almost all renovations are efficient for apartment blocks built before 1956 and between 1956-1970 in original state, as these building types have the highest energy use before renovation. However, improving the building envelope to TEK10 or passive house level, as well as installing air-to-air heat pumps as supplementary measures are seen profitable for all the building types analyzed over a period of 36 years.

Installation of a balanced ventilation system is only estimated to be profitable for apartment blocks built before 1956 and between 1956-1970 in original state. However, when upgrading the building envelope to passive house level it is recommended to install a balanced ventilation system to ensure a satisfactory air quality (Thomsen & Berge, 2012). Since there is high willingness to pay for comfort it is anticipated that installation of a balanced ventilation system combined with a passive house envelope upgrade is realistic for all building types even though the net present value is up to 400 NOK/m^2 BRA higher than for base case (no energy-related upgrades to the building).

Sammendrag

Tre bygningstypologier er blitt analysert i denne rapporten. Den første bygningstypologien tar for seg leilighetsblokker bygd før 1956, den andre tar for seg leilighetsblokker bygd i perioden 1956-1970, mens den siste tar for seg leilighetsblokker bygd i perioden 1971-1980. En litteraturstudie i forhold til hvordan utviklingen av norske bygninger har vært i løpet av årene er blitt gjennomført og de tre bygningstypologiene er definert som typiske bygg fra hver angitte periode.

Modellen som blir brukt til å beregne bygningens energibruk til romoppvarming er basert på TABULA metodologi, men er konstruert som en energibalansemodell basert på prinsippene i en materialstrømsanalyse. Denne modellen blir brukt til å beregne byggenes energibruk før og etter renovering. To bygningstilstander før renovering blir analysert for hver periode; original tilstand og historisk oppgradert tilstand. Dette blir gjort siden en stor del av bygningene bygd før 1980 har gjennomgått en form for renovering allerede, og energisparingspotensialet ved å innføre energieffektiviseringstiltak er mindre for disse historisk oppgraderte byggene enn for de i original tilstand. En kostnadsanalyse som bruker prinsippene til en netto nåverdisvurdering er utført over en periode på 36 år for ulike renoveringspakker. For å estimere hvordan fremtidens totale energibruk for leilighetsblokker bygd før 1980 vil være er det laget en scenariomodell som henter inputs fra en segmentert bygningsmasse modell (se kapittel 3.3.1) og energiberegningsmodellen (se kapittel 3.1).

Reduksjonspotensialet ved å oppgradere en typisk bygning bygd før 1956 fra original tilstand til TEK10-nivå er 68 % for romoppvarming. Oppgradering videre til passivhusnivå fører til at reduksjonspotensialet økes til 81 %, noe som viser at det er store forbedringspotensialer for denne bygningstypen. Imidlertid vil kun et mindretall (16 %) av leilighetsblokkene fra denne perioden være i original tilstand, noe som betyr at et mer realistisk reduksjonspotensial vil være fra historisk renovert tilstand til TEK10- eller passivhusnivå. Reduksjonspotensialet for en TEK10-oppgradering av bygget vil da være 46 %, mens en passivhus-oppgradering av bygget vil gi et reduksjonspotensial på 67 %. Generelt kan det sies at energisparingspotensialet minker etter hvert som kvaliteten på byggene i original og historisk oppgradert tilstand forbedres. Leilighetsblokker bygd mellom 1971 og 1980 har det minste energisparingspotensialet ettersom kvaliteten før renovering er forholdsvis bra. Dette gjør også disse bygningstypene minst lønnsomme for ulike renoveringsprosjekter. Nesten ale renoveringer er vist lønnsomme for leilighetsblokker bygd før 1956 og mellom 1956-1970 i original tilstand siden disse bygningstypene har høyest energibehov før renovering. Imidlertid vil det å oppgradere bygningskroppen til TEK10-nivå og passivhusnivå kombinert med installasjon av luft-til-luft varmepumpe være økonomisk lønnsomt for alle bygningstypene over en periode på 36 år.

Installasjon av balansert ventilasjonssystem er kun lønnsomt for leilighetsblokker bygd før 1956 og mellom 1956-1970 i original tilstand. Det er imidlertid anbefalt å installere et balansert ventilasjonsanlegg i bygget når bygningskroppen oppgraderes til passivhusnivå for å sikre tilfredsstillende luftkvalitet (Thomsen & Berge, 2012). Siden det er stor vilje til å betale for komfort er det antatt at installasjon av balansert ventilasjonsanlegg vil være realistisk for alle bygningstypene til tross for at netto nåverdi er opptil 400 NOK/m^2 BRA høyere enn for referansescenarioet (ingen energirelaterte oppgraderinger).

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Key terms and variables

This chapter describes the meaning of common key terms and variables used in this report.

Key terms

BRA	Is the Norwegian abbreviation of utility floor space and includes all used floor area in the building. If a building has three floors the BRA will be the sum of the floor area in each floor [m^2] (Kommunal- og regionaldepartementet, 2010)
$U - value$	Is the thermal transmittance and is a measure of heat loss in a building element such as a wall, floor or roof. A high U-value therefore corresponds to high transmission losses through the building envelope, while a low U-value corresponds to low transmission losses through the building envelope [W/m^2K] (Brennan, 2013)
MFA	Material flow analysis
GWP	GWP stands for global warming potential and is a metric used to compare the greenhouse effect of various components. GWP is defined as the sum of climate forcing of 1 kg emission of climate-driver relative to the sum of the climate forcing from 1 kg of CO_2. Methane has for instance a GWP value of 21 CO_2-equivilents since it has 21 times as strong global warming effect than CO_2 (Miljødirektoratet, 2013).
WHO	World health organization
LCC	Life cycle costing
NPV	Net Present Value

Key variables

$A_{env,i}$	Is the area of building envelope i, where i can be wall, window, roof, door or floor [m^2]
$A_{window,i}$	Is the window area at orientation i, where i can be horizontal, east, west, north or south [m^2]
a_H	A time dependent parameter used to find the gain utilization factor ($\eta_{h,gn}$) Can be found by following equation: $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ [-]
$a_{H,0}$	= 0.8 (Loga & Diefenbach, 2012)

$\alpha_{nd,h,i}$	Fraction of heat generator i for space heating system [-]
$\alpha_{nd,w,i}$	Fraction of heat generator i for domestic hot water system [-]
b_{tr}	Adjustment factor soil [-]
c_m	Internal heat capacity (used to calculate time constant of the building, τ) [Wh/m^{2}K]
$c_{p,air}$	Volume specific heat capacity of air [Wh/m^{2}K]
d_{HS}	Length of heating season [days/year]
$e_{g,h,i}$	Heat generation expenditure factor of heat generator i for space heating system [-]
$e_{g,w,i}$	Heat generation expenditure factor of heat generator i for domestic hot water system [-]
F_{sh}	Reduction factor external shading. One value for horizontal orientation (windows at roof) and one value for vertical orientation (windows at external walls) [-]
F_F	Frame area fraction of a window [-]
F_W	Reduction factor, considering radiation non-perpendicular to the glazing [-]
F_{nu}	Dimensionless correction factor for non-uniform heating
$g_{gl,n}$	Total solar energy transmittance for radiation perpendicular to the glazing. Describes how much of the solar radiation that gets absorbed by the windows [-]
$h_{room,ve,ref}$	Ventilation reference room height (normally set to 2.5 m) [m]
H_{ve}	Overall heat transfer coefficient by ventilation [W/K]
H_{tr}	Overall heat transfer coefficient by transmission [W/K]
$I_{sol,i}$	Average global irradiation on surfaces with orientation i during heating season [kWh/m^{2}year]
ϕ_{int}	Average thermal output of internal heat sources [W/m^2]
ϑ_{int}	The internal temperature (set-point temperature for space heating) [°C]
ϑ_e	The temperature of the external environment (average value during heating season) [°C]

$n_{air,use}$	Average air change rate during heating season, related to the utilization of the building [1/h]
$n_{air,infiltr.}$	Air change by infiltration [1/h]
$\eta_{ve,rec}$	Efficiency of ventilation heat recovery
$\eta_{h,gn}$	Gain utilization factor for heating (see chapter 3.1) [-]
$q_{nd,w}$	Annual energy need for domestic hot water per m^2 reference floor area (BRA) [kWh/m^2year]
$q_{s,w}$	Annual heat loss of the DHW storage per m^2 reference floor area (BRA) [kWh/m^2year]
$q_{d,w}$	Annual heat loss of the DHW distribution system per m^2 reference floor area (BRA) [kWh/m^2year]
$q_{g,w,h}$	Recoverable heat loss of the heat generators for domestic hot water [kWh/m^2year]
$q_{d,h}$	Annual effective heat loss of the space heating distribution system per m^2 reference floor area [kWh/m^2year]
$q_{s,h}$	Annual effective heat loss of the space heating storage system per m^2 reference floor area [kWh/m^2year]
$q_{d,w,h}$	Recoverable heat loss of the domestic hot water distribution system per m^2 reference floor area [kWh/m^2year]
$q_{s,w,h}$	Recoverable heat loss of the domestic hot water storage system per m^2 reference floor area [kWh/m^2year]
$t_{døgn}$	Hours per day, given as 0.024 kh/day
τ	Time constant of the building ($\tau = \frac{c_m \cdot A_{C,ref}}{H_{tr}+H_{ve}}$) [h]
y	Heat balance ratio ($= \frac{Q_{sol}+Q_{int}}{Q_{ht,ve}+Q_{ht,tr}}$) (see chapter 3.1 for more information of flows) [-]
ΔU_{thr}	Surcharge on all U-values (Thermal bridges) [W/m^2K]

1 Introduction

In 2009 the Norwegian building sector contributed to 40 % of the total energy use when energy use offshore is excluded (Arnstad, 2010). Since the end of the 1990s the energy use in dwellings have stabilized even though the population have increased. More energy efficient buildings, a warmer climate, higher energy prices and increased use of heat pumps can explain this development. The Norwegian government has set a target to increase the renewable energy production by 30 TWh in 2016 compared to the level in 2001. The government has also set a goal to implement passive house standard as the national building standard in 2015 (Grini, 2012).

This thesis is connected to EU's Intelligent Energy Europe funded Episcope project, which is a follow-up of the recent TABULA project. The aim of the project is to identify the potential for energy savings in existing dwellings. The TABULA project uses a European standard reference calculation procedure for determining the heat need and the delivered energy demand. The goal of the TABULA project is to determine important parameters that play an important role for the energy consumption in buildings. The calculation method is kept as simple as possible to ensure that experts in each country easily can understand the content. This means that average values are used were applicable to reduce the need of more detailed methods (Loga & Diefenbach, 2012).

A building's energy need for heating is dependent on the quality of the building envelope, the heating system, and the domestic hot water system (Loga & Diefenbach, 2012). In this Master thesis it is focused on the energy use for space heating and domestic hot water in residential buildings. The energy need for cooling, lighting and electrical equipment is not evaluated in the report, but may be of great interest at a later stage. The calculation method used to calculate the energy need is based on the TABULA calculation method, but is made as a material flow analysis model specified for Norwegian conditions. This is done to have better control over the results from the study. Several countries like Denmark and Sweden have already developed their own building typologies in TABULA. The aim of this Master thesis is to develop typologies and energy demand modeling of a specified Norwegian building stock, which can later be used as an input to TABULA.

The Norwegian building stock has a huge improvement potential as the majority of existing dwellings are built before 1980 (Prognosesenteret AS & Entelligens AS, 2012). In this thesis it is focused on apartment blocks built before 1980, and the three time periods analyzed are:

- ← 1956
- 1956-1970
- 1971-1980

A case study for a typical apartment block from each of these time periods is examined and an energy assessment as well as a life cycle costing (LCC) analysis before and after renovation is completed for each case.

Fourteen different renovation packages are examined and a description of each of the renovation packages is given in chapter 3.2.2. Based on results from the LCC analysis the most appropriate renovation packages are chosen and evaluated in a future scenario model to see how the energy use for this part of the Norwegian dwelling stock can be in the future. A worst case scenario, a best case scenario and a “realistic” future scenario is considered (see chapter 4.3).

The following chapter includes a literature study of a typical development for the specified building type. Current and future national and EU regulations are also given in this chapter, as well as common refurbishments technologies. A short introduction to the EPISCOPE/TABULA project and an introduction of common analysis methods used in the report are also given.

Chapter 3 describes the methodology used to calculate the energy flows, the elements necessary to perform a life cycle costing analysis, as well as the methodology used to estimate the future accumulated energy use and carbon emissions in apartment blocks built before 1980. This chapter includes detailed information of the models used as well as a thoroughly review of important parameters used. The results from the energy calculations before and after renovation, as well as the results from the LCC analysis are given in chapter 4. This chapter includes a sensitivity analysis of parameters that are qualified as important for the end result and that are given with somewhat high uncertainty. Chapter 4.3 gives a future estimation on how the development can be when it comes to future energy need and carbon emissions related to utilization of Norwegian apartment blocks built before 1980.

2 Literature study

2.1 Future Energy situation and the challenges of climate change

Prognosis for expected energy demand and delivery are made each year by the international energy Agency, IEA. Primary energy is defined as the amount of energy in form of oil, gas, coal, bio etc. that is required to produce 1 unit of delivered energy. The energy use is expected to increase which gives a major pressure on the world's energy resources in the future (Dokka, Wigenstad, & Lien, 2009).

Oil production has most likely reached its peak, which indicates that the world's energy consumption has to decrease or the renewable energy production has to increase significantly to be able to cover the future energy demand (Randers, 2006).

The Norwegian greenhouse gas emissions are expected to increase from 50 Mton CO_2-equvielents in 1990 to 70 Mton CO_2-equivilents in 2060. UN Climate Change Convention have decided that the overall global mean surface temperature increase should not exceed 2°C above pre-industrial level in order to limit high risks, including irreversible impacts of climate change (Randers, 2006). As long as the concentration of climate gasses in the atmosphere do not exceed 400-450 ppm this goal can be reached. Today, the concentration is about 380 ppm, which is an increase of 100 ppm since pre-industrial time. To be able to stabilize the greenhouse gas concentration in the atmosphere it is estimated that the global emissions have to be reduced by minimum 50 % within 2050 (Randers, 2006). This goal is unfortunately a bit unrealistic due to necessary economical and social development in developing countries. However, it is very important that industrialized countries, like Norway, start developing the technology so that energy- and emission efficient solutions are cheaper to use in the future.

To be able to reach an emission reduction as illustrated in Figure 1, drastic actions on several areas have to be done. The electricity price has to be increased significantly and the Government has to introduce a number of political incentives that promotes solutions with a low carbon footprint.

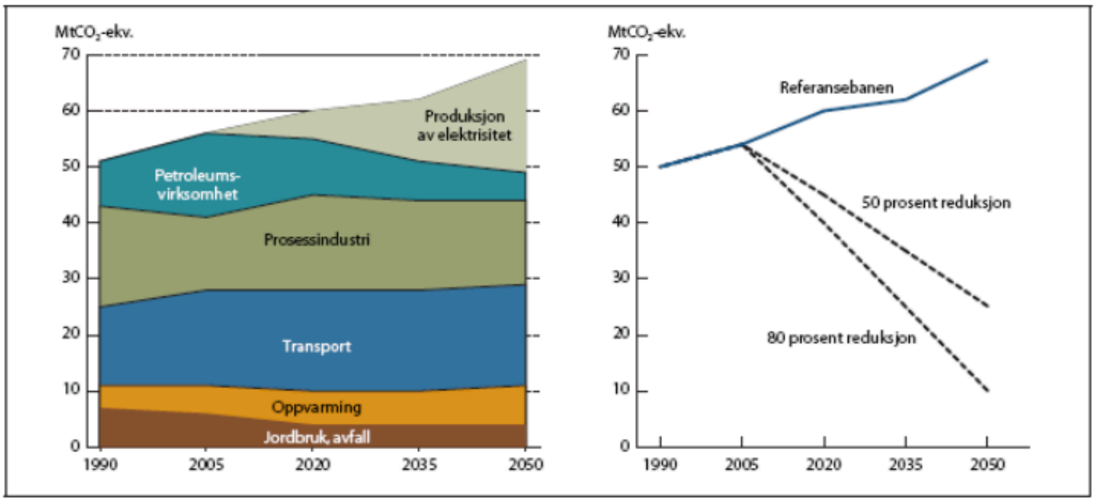


Figure 1: Expected green house gas emissions in Norway at reference scenario (business as usual) compared with 50 and 80 % emission reduction (Randers, 2006).

A big part of the energy demand is estimated to come from the building sector, and it is therefore important to make buildings as efficient as possible. The first step in making a building efficient is to construct a tight building envelope with low U-values. The technical installations should then be made as efficient as possible, for instance by including systems with heat recovery. The next step, see Figure 2, is to use as much “free energy” as possible. This includes utilization of solar and internal gains. The building’s energy need after subtraction of “free energy” should be covered as far as possible by CO_2-neutral energy sources such as wind power, hydropower and heat pumps. Grid-based energy can be used if all renewable possibilities are considered not suitable for the specified building (Dokka, Wigenstad, & Lien, 2009).

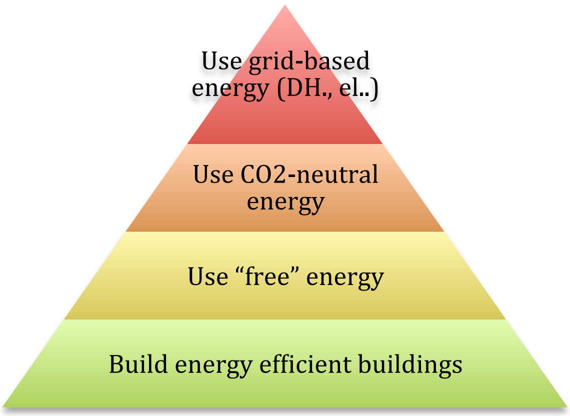


Figure 2: Strategy to reduce energy need and climate gas emissions

Today, operation of buildings contributes to approximately 40 % of the total energy use in Norway. Energy efficiency in buildings can contribute to a reduction in green house gas emissions as well as increasing the security of energy supply in Norway (Arnstad, 2010).

It has been shown in several international studies that energy efficiency measures are the simplest and cheapest mitigation. Energy efficiency measures in buildings contribute to replace polluting energy sources in other sectors by reducing the need for new power generation. To achieve the goal of higher energy efficiency in buildings it is important that the government set specific goals on how to achieve them. The Norwegian building stock uses approximately 80 TWh per year, and it is realistic to assume that this energy use easily can be reduced with 10 TWh by the year 2020 if the right measures are introduced. If several energy efficiency measures are introduced to the existing building stock and stricter requirements are set for new buildings it can be possible to reduce the energy for the operation of buildings by 50 % by the year 2040. However, to achieve this goal there has to be a significant national lift when it comes to regulatory changes, financial support schemes, skills upgrading and behavioral changes (Arnstad, 2010).

To increase energy efficiency the government has to implement several changes. To ensure the quality of performance of energy measures in buildings it is important to develop safe and solid solutions. Since many renovation projects can be costly for the owner it is important to introduce financial support schemes that gives extra support for the building owners. For new buildings the regulations have to become stricter, and EU have established a goal that says that all new constructions should be almost zero energy buildings by the year 2020. One challenge for the society when it comes to increasing energy efficiency is that most of the people working in the construction industry do not have sufficient competence when it comes to energy efficient solutions. By establishing a systematic education and training program to the employees in the construction industry it will be easier to reach the goal of increased energy efficiency in buildings (Arnstad, 2010).

KRD propose that several measures should be put in action to facilitate renovation projects that lead to low energy use in buildings. It is proposed that low energy level should be a requirement when a building gets completely renovated in 2015. In 2020 passive house level should be set as the requirement. Completely renovation is defined as a renovation that costs more than 25 % of the buildings value and where 25 % of the building envelope is completely renovated. The government should also set a requirement of using only energy efficient building components in all renovation projects from the beginning of 2015. The KRD project team also propose that there should be a requirement of individual energy meter in each apartment by the year 2015 to make it easier for the consumer to control the consumption. The government should also establish predictable grant schemes for energy efficient renovation to make energy efficient solutions more attractive (Arnstad, 2010).

Financial barriers that make it difficult to implement energy efficiency measures are low energy prices, increased investment cost for energy efficient measures, and low degree of economic incentive for the building owner. It is therefore important to highlight that energy efficiency measures increase the value of the building as well as it gives a reduction in energy use (Arnstad, 2010).

There are also several cultural barriers that needs to be considered and that have to be broken if reduction in energy use should become more realistic. Today there is lack of technical knowledge and competence on how to perform several energy efficiency measures. Because of this it is easier to continue with the technology that the construction company is comfortable with, as there are to many risks, both economically and qualitatively, with new solutions. However, this is not how changes appear. It is therefore important that the construction companies get the right competence, so that energy efficient solutions are easier to implement. And as the competence increase, the investment cost connected to these measures decreases (Arnstad, 2010).

It is important to show the severity of the climate crisis and reveal the disadvantages it can have on next generations if no changes are made today. The buildings of tomorrow should have extremely low energy need as well as a good indoor climate. They should also use environmental friendly materials and have a long lifetime. To be able to satisfy these requirements it will require a lot both financially and technologically (Arnstad, 2010).

2.2 Current national and EU regulations

The current Norwegian technical regulation was renewed in 2010. The first national building regulation came in 1949 as an attempt to reduce the heat loss from newly constructed buildings. As the technology improved and the need for energy efficient buildings increased the building regulation became stricter. It is natural to assume that buildings built after 1949 satisfies the regulations made in 1949. During the time period 1949-2013 four new regulations have been made, one in 1969, one in 1985 (which was later revised in 1987), one in 1997, and one in 2007 (which was later revised in 2010) (Hille, Simonsen, & Aall, 2011).

Assuming that buildings are built after the regulations can more or less be expected for buildings built after 1987. However, in the first decades after the first regulation was implemented many buildings were probably built better than what the regulation required since the building regulation of 1949 did not have strict requirements when it came to insulation of walls etc. It is therefore appropriate to assume that a significant part of the building stock from the period 1950-1985 are insulated better than what was required by the building regulations (Hille, Simonsen, & Aall, 2011).

The current technical regulation has requirements when it comes to air quality and energy requirements in buildings. When it comes to ventilation it is required that the ventilation system is adapted to the pollution and moisture load in the room. The minimum requirement for ventilation airflow in a residential building is 1.2 m^3 fresh air per hour per m^2 floor area when the building is in use and minimum 0.7 m^3 fresh air per hour per m^2 floor area when the building is not in use. In kitchen and sanitary rooms there should be an exhaust unit with satisfactory efficiency (§13-1 and §13-2) (Kommunal- og regionaldepartementet, 2010).

When it comes to the building envelope it is required that transmission heat loss should be held to a minimum. The U-value for external walls, windows, roof and floor should not exceed 0.18, 1.2, 0.13 and 0.15 W/m^2K respectively. The window and door area should not exceed 20 % of heated usable area (BRA). For an apartment block the building regulation of 2010 requires that the net energy consumption should not exceed 115 kWh/m^2 heated BRA per year (Kommunal- og regionaldepartementet, 2010).

Table 1 shows the requirement given in TEK10 and the requirements that satisfy the passive house standard.

Table 1: Technical regulations 2010 and passive house requirement. (TEK10) (NS3700, 2013)

	TECHNICAL REGULATIONS (2010)	Passive house requirement
Transmission heat loss:		
U-value external walls	$\leq 0.18\ W/m^2K$	$0.10 – 0.12\ W/m^2K$
U-value window/door	$\leq 1.2\ W/m^2K$	$\leq 0.80\ W/m^2K$
U-value roof	$\leq 0.13\ W/m^2K$	$0.08 - 0.09\ W/m^2K$
U-value floor	$\leq 0.15\ W/m^2K$	$0.08\ W/m^2K$
Share of window- and door area	≤ 20 % of heated usable floor area (BRA)	≤ 20 % of heated usable floor area (BRA)
Normalized thermal bridge value	$0.06\ W/m^2K$ (this value is per m^2 BRA)	$0.03\ W/m^2K$ (this value is per m^2 BRA)

Infiltration and ventilation heat loss:		
Leakage rate	1.5 air exchanges per hour	0.6 air exchanges per hour
Yearly temperature efficiency of a heat exchanger in a ventilation system	≥ 70 %	≥ 80 %
Other regulations:		
Specific fan power in a ventilation system (SFP)	2,5 kW/(m^3/s)	1.5 kW/(m^3/s)

Today all buildings have to fulfill the technical regulations of 2010. To get qualified as a passive house the transmission and ventilation losses have to be reduced further. The name "passive house" is used because passive measures are used to reduce the energy need. These kinds of measures include extra insulation in walls, roof and floor, which gives a very good tightness of the building envelope. Passive houses are also constructed with high heat recovery of the ventilation heat. Since the building envelope is very tight it can be more challenging to achieve good air quality inside the house. Heat recovery in the ventilation system is therefore a must when achieving good air quality combined with low net energy use (Lavenergiprogrammet, 2013).

A passive house can be a bit more expensive to build than a normal TEK10-house due to more expensive windows and higher material use in form of higher amount of insulation. A passive house will however have lower net energy use than a TEK10-building. The net energy savings during the building's lifetime is therefore higher for a passive house.

The technical regulation of 2010 requires that buildings over 500 m^2 heated BRA should be constructed in a way that makes it possible to cover 60 % of the heating demand by other energy sources than direct electricity or fossil fuels. This requirement can be achieved by installing a solar collector or a heat pump (Kommunal- og regionaldepartementet, 2010).

The regulations of 2010 can be fulfilled in two ways; either the building must fulfill all the requirements in Table 1, or the net energy consumption in reference climate have to be less than 115 kWh per m^2 heated usable floor area for an apartment block. The U-values for external walls, windows, roof and floor must though not exceed 0.22, 1.6, 0.18 and 0.18 respectively and the leakage rate should not exceed 3 air changes per hour (Kommunal- og regionaldepartementet, 2010).

2.3 Future national and EU regulations

It has been studied how much energy that can be saved by establishing stricter regulations not only for new buildings but also for existing buildings. When a building component is replaced or maintained there should be a minimum requirement of the quality of the improvement. Some components should follow a minimum standard regardless of the financial profitability of the measure, while others should only hold a minimum requirement when the measure is privately profitable and technically feasible. A study done by Asplan Viak showed that the financial benefits of choosing energy efficient solutions for small renovation projects varies so much that it is difficult to base a general component requirement on financial profitability. However, improvement of windows to a level better than TEK10 is seen to be privately profitable. Improvement of windows is also a simple measure as it is easy to identify the building component. The production of new windows can also be done in factories, which reduce the costs connected to the construction area. It is recommended that the U-value requirement for windows get reduced to 0.8 - 0.9 W/m^2K (Arnstad, 2010).

Research has shown that the energy saving potential is largest for old buildings as the energy need often is high. Newer buildings with a lower energy use should also be improved, but the oldest buildings should be the priority. Grant schemes or subsidies should optimally be targeted to components with a large energy saving potential, identifiable components like windows, profitable replacements and components with a marked potential (Arnstad, 2010).

In 2011 the European Commission made a proposal for an Energy Efficiency Directive that would work with the issues of the rising energy consumption in EU. The directive have decided to set energy saving obligations for member states, and a large part of the responsibility for energy efficiency will accrue to the construction industry. The energy suppliers are though required to implement energy saving measures equivalent to 1.5 % of the total energy sales per year. Furthermore, 3 percent of all government buildings over 500 m^2 (250 m^2 from 2015) should be renovated to an energy standard of regulation level each year (Energieffektiviseringsdirektivet, 2013).

The European Commission has also given a requirement that involves Energy producers to encourage consumers to reduce the energy consumption through energy saving measures, like replacement of old water heaters and improvement of the building envelope. The Energy Efficiency Directive will make it easier for consumers to control energy consumption through better information from electricity meters. As a consequence of better electricity meters the consumption can decrease since the consumer has better control over the consumption. Companies that deliver components or services that can decrease energy consumption should also go through a certification so that optimal quality and technical competence is fulfilled. The EU commission has also proposed a suggestion of introducing the funding program “Build Up skills” so that the need for increased knowledge about energy efficiency measures are met (Energieffektiviseringsdirektivet, 2013). By 30th of April 2014 all member countries in EU should have established a long-term strategy to mobilize investment in rehabilitation of residential, commercial and public buildings (Europaportalen, 2013).

2.4 Typologies and dynamics of aggregates building stock

In 2011 the Norwegian occupied building stock consisted of 258 millions m^2 BRA, where 169 millions m^2 were detached houses, 47 millions m^2 were small dwellings and 42 millions m^2 were apartments (Prognosesenteret AS & Entelligens AS, 2012). During the last 20 years major renovations have been done and 52 % of the total residential area has had one or more renovations like replacement of windows and extra insulation of walls. When demolition of the existing building stock is taken into consideration new residential units are estimated to stand for about 10 % of the overall dwelling stock area in 2020. This is not a very big number, which means that the majority of the building stock in 2020 will be existing buildings (Prognosesenteret AS & Entelligens AS, 2012).

70 000 new apartments have been built since 2006, and today apartment blocks stands for about 22 percent of the total Norwegian dwelling stock (Statistisk Sentralbyrå, 2013). Based on information from Enova an estimation of average area per apartment has been made for each time period evaluated in this thesis (see Table 2).

Table 2: Apartment blocks specification throughout time (Prognosesenteret AS & Entelligens AS, 2012)

Apartment type	Number of occupied dwellings	%-amount of all apartments	Utility floor space (m2)	%-amount of total apartment area	Average area per dwelling unit (m2)	Number of units per block	Number of blocks
Before 1956	161 554	27%	11 444 245	27%	71	8	20 194
1956-1970	106 324	18%	7 133 096	17%	67	16	6 645
1971-1980	90 441	15%	6 739 001	16%	75	24	3 768

When the standard of the different building typologies is taken into consideration different RME works (ie. renovation, reconstruction and extension of existing dwellings) that affects the building's energy need has to be included. The standard of the building components given in the report includes both original values and values after historical refurbishments.

Estimation on how many apartments that have been refurbished from each time period are given in Figure 3. As shown in the figure 84 % of the buildings built before 1956 have already gone through some sort of renovations. However, the improvement potential for the 16 % that is not refurbished is most likely huge.

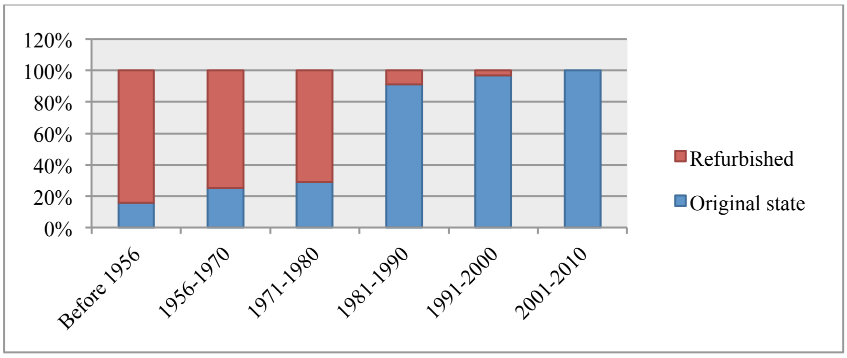


Figure 3: Status on existing dwellings, 2010 (Prognosesenteret AS & Entelligens AS, 2012)

The most common construction material used in Norwegian dwellings throughout time is wood. However this is mainly for detached houses and other small dwellings. For apartment blocks and other larger buildings there have been some regulations due to fire risk that has limited the use of wood. The building size is therefore crucial when examining what kind of material that is used. For apartment blocks and terraced houses about 54 % of the buildings use concrete as their main material, while 23 % and 22 % use wood and steel respectively (Prognosesenteret AS & Entelligens AS, 2012).

Apartment blocks are defined as buildings that averagely consist of 18 apartments and four floors. However a more specific number of apartments per block are given for each time period (see Table 3). Apartments stand for about 16 % of the total dwelling stock area (BRA) (Prognosesenteret AS & Entelligens AS, 2012). An estimation of the building size (ground area) is estimated based on the fact that an apartment block consists of four floors.

Table 3: Estimation of ground area and size of apartment blocks built before 1980 (Prognosesenteret AS & Entelligens AS, 2012)

	Average area per dwelling unit (m^2)	Number of units per block	Number of floors	Size of building (length x width, m)	Heated floor area (BRA, m^2)	Ceiling height (m)
Before 1956	71	8	4	15.97 × 8.87	568	2.8
1955-1970	67	16	4	34.18 ×7.70	1072	2.7
1971-1980	75	24	4	39.79 × 11.24	1800	2.5

There have been several constructional development trends, and the most important ones that have influenced the annual energy demand are mentioned in this chapter. Early in the 1950s mineral wool became commercially available, and lightweight timber frame was introduced as a new construction method that replaced heavy framework and timber. For bigger buildings the period before 1956 was described as a transition period where the same construction system was used, but light clinker concrete, poured concrete, concrete beams and steel beams were introduced as materials (Prognosesenteret AS & Entelligens AS, 2012).

Typical for apartment blocks built during the time period 1956-1970 was increased use of retention walls and floor dividers in concrete instead of brick houses with retention walls in bricked bituminous and floor dividers mainly in wood. The building regulation in 1949 had stricter requirements for houses made in wood than for houses made in concrete or rock material, and since all apartment blocks were mainly made in concrete the U-value requirement was very low. This explains why apartment blocks built in this period generally have higher U-values on exterior walls than detached houses from the same period. In 1969 TEK69 came, which had several requirements for insulation in dwellings aiming to decrease the energy use. In 1978-80 there was an international energy crisis that led to stricter building regulations in 1983 with further revision in TEK85-87. Further up buildings built during the time period 1990-1997, 1998-2010 and after 2010 had to fulfill the building regulations of 1987, 1997 and 2010 respectively. It must be mentioned that the values in these regulations only give a minimum value and that some buildings are built with better insulation etc. than what the regulations required (Prognosesenteret AS & Entelligens AS, 2012).

2.4.1 Technical requirement for apartment blocks throughout time

A summary of the technical regulations throughout time is given in Table 4. As the table show the U-value requirements was not very strict in 1949 compared to the regulations of 2010 (see chapter 2.2).

Table 4: Technical regulations throughout time (Bøhn & Ulriksen, 2006)

Building component	**U-value requirement (W/m2K)**				
	Regulation 1949	Regulation 1969	Regulation 1985	Regulation 1987	Regulation 1997
Wall	0.93-1.16	0.58-1.28	0.45	0.30	0.22
Roof	0.93	0.46-0.58	0.23	0.20	0.15
Floor	-	0.46	0.23-0.30	0.20-0.30	0.15
Window	-	-	2.10-2.70	2.40	1.60

Since the building regulation of 1949 approved quite high U-values, many buildings during the time period 1950-1970 were built with better building envelope then what the regulation required.

2.5 Annual energy demand and important influencing factors

The energy use in buildings increased during the period 1950-1990 due to mainly increased comfort level. However, from 1990 the energy use stabilized. One of the main reasons for this stabilization is that the development in dwelling area per person stabilized. If the dwelling area per person had continued increasing in the same manner as before 1990 the total dwelling area today would be about 350 millions square meters, which is approximately 36 % larger than the actual level today. Another reason for this stabilization is more energy efficient buildings, which lead to lower energy use per square meter. The most important contributor on this field is the improvements done on the thermal envelope in old buildings. Other important contributors to energy efficiency are implementation of heat pumps and reduction in heat loss due to more efficient heat generators (Hille, Simonsen, & Aall, 2011).

The third most important impact factor is warmer climate. Figure 4 shows the development during the last 60 years (Hille, Simonsen, & Aall, 2011).

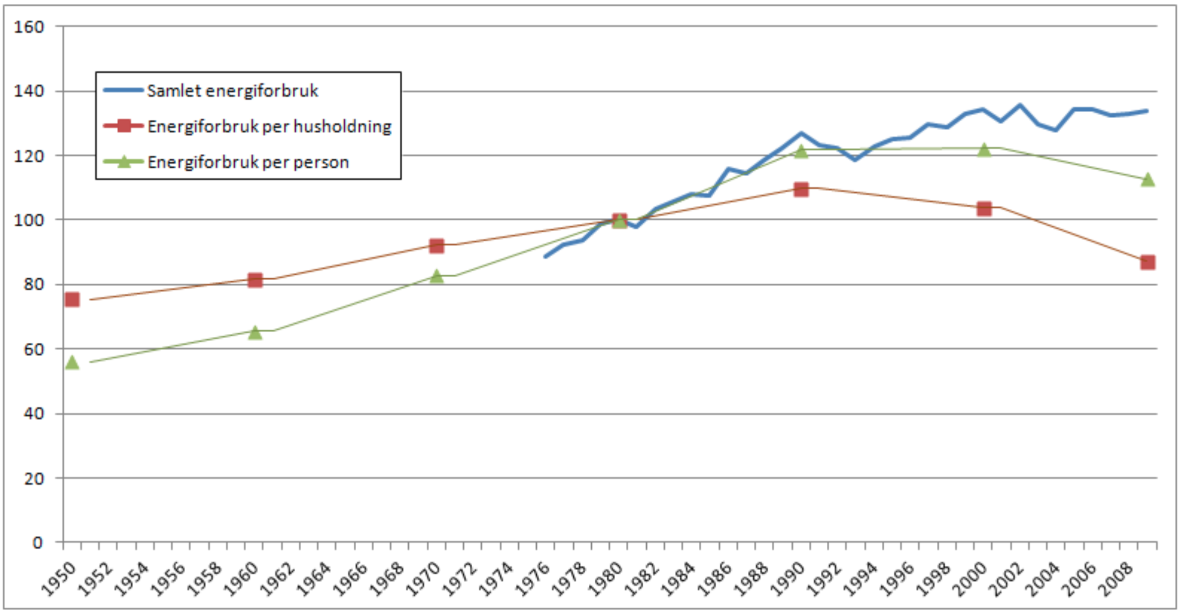


Figure 4: The relative development of the temperature dependent energy use in Norwegian households during the period 1950-2009 (Hille, Simonsen, & Aall, 2011)

Important direct influencing factors are:

- Residential area
- Building type
- Building envelope
- Indoor temperature
- Energy use for domestic hot water
- Energy use for lighting and electrical equipment
- Choice of heating system
- Use of heat pumps

Important indirect influencing factors:

- Changes in outdoor temperature
- Demographic changes
- Economical conditions
- Technological development
- Changes in knowledge, attitude and preferences
- Political incentives

2.6 Passive houses, indoor air quality and health

The main function of a building is to provide an area that is comfortable and that satisfy the owner's need. How the building is constructed is crucial for the human health. A building that is constructed in the right manner can lead to health benefits and protection. Buildings that are constructed wrong can lead to negative health effects, like headache, dry eyes, allergy, lung cancer etc. Common reasons for indoor air quality problems are technical problems, pollutions that are added to the buildings or that don't get ventilated away, dust and dirt that are applied /not washed away, moisture damage, and radon pollution (Thomsen & Berge, 2012).

Typical characteristics for a passive house building are a tight building envelope, low heat losses through infiltration, and reduced heat loss due to ventilation because of a heat recovery unit. There is no doubt that building a passive house is good for the energy situation because it general consume little energy, but there are some health concerns related to passive houses and indoor environment. Since the walls are constructed with more insulation there is less natural ventilation, which general requires installation of a balanced ventilation system to remain a satisfying air quality in the building (Thomsen & Berge, 2012).

The Passive House Institute have defined that the air change rate due to ventilation never should be lower than 0.3 vicissitudes per hour to keep a decent air quality. TEK10 requires an air change rate of 1.2 m^3/h per m^2 heated floor area, which correspond to approximately 0.4 vicissitudes per hour for the buildings analyzed in this study. As long as it is installed a balanced ventilation system that makes sure that the air is ventilated properly a passive house will be as good as or better than a traditional house. (Thomsen & Berge, 2012). It is reported that a passive house actual leads to several benefits when it comes to indoor environment if constructed and operated properly. The thermal comfort during winter increases due to warmer surfaces. There is also reduced risk for condensation and formation of mold on interior surfaces because of a tighter envelope. If a proper ventilation system is installed there will also be decreased pollution in the air due to regular and continuous air renewal (Thomsen & Berge, 2012).

Negative impacts a passive house can have on the indoor climate are mostly related to defects connected to construction and operation. Among these are increased vulnerability when it comes to moisture damage in the construction due to increased insulation thickness, microbiological growth in ventilating systems caused by incorrect or inadequate maintenance, as well as overheating in the summer due to lack of shading devices. Except for these possible negative impacts there are seen few negative sides with passive houses (Thomsen & Berge, 2012).

2.7 Common technologies and design solutions in new construction and renovation projects

2.7.1 Solar collectors

Solar energy is accessible almost everywhere on the planet and provides a huge energy potential. It is also one of the most environmental friendly energy sources as it is based on natural energy from the sun. The earth receives approximately 15 000 times more energy from the sun each year than what is being consumed by humans. If efficient technological solutions that could use all this energy had been developed, the world's energy crisis would have been solved. Even in cold Norway the earth receives 1500 times as much as what is consumed (Andersen I., 2008).

Today there are different technological solutions that utilize the solar energy. However, none of them can utilize the entire solar potential. But both solar cells and solar collector are becoming more and more efficient and is considered satisfactory. Solar cells convert the solar energy into electricity, while solar collectors utilize the thermal energy from the sun. Research have shown that utilization of the solar heat to heating purposes in buildings are simple, environmental friendly and economical profitable. In the future when the electricity price is expected to increase these solutions can become more and more desirable (Andersen I., 2008).

In Norway the annual solar radiation varies from approximately 700 kWh/m^2 in the north to 1100 kWh/m^2 in the south. It is however huge variations between summer and winter. It is therefore not possible to use solar collectors as the only heating source unless there are possibilities to store the energy from summer to winter. For passive houses that only have a space heating demand during the winter when the solar radiation is low (see Figure 5) it is not possible to use solar collectors to cover the entire space heating demand. However, since the domestic hot water use is constant during the year it is very beneficial to use solar collectors to cover this heating demand. It is estimated that solar collector are able to cover approximately 60 % of the heating demand (Andersen I., 2008).

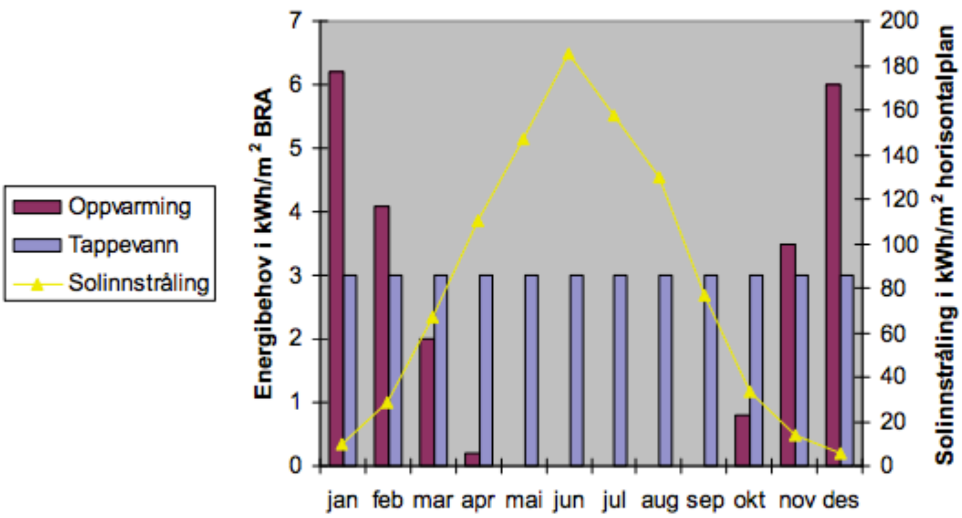


Figure 5: Monthly energy need for space heating and domestic hot water for a low energy building in Oslo. Monthly solar radiation in Oslo is also marked (see yellow line) (Andersen I., 2008).

A typical solar collector system for domestic hot water heating is built up as shown in Figure 6, and basically consists of the following components:

- Solar collector
- Heat storage tank
- A distribution system
- Control automation

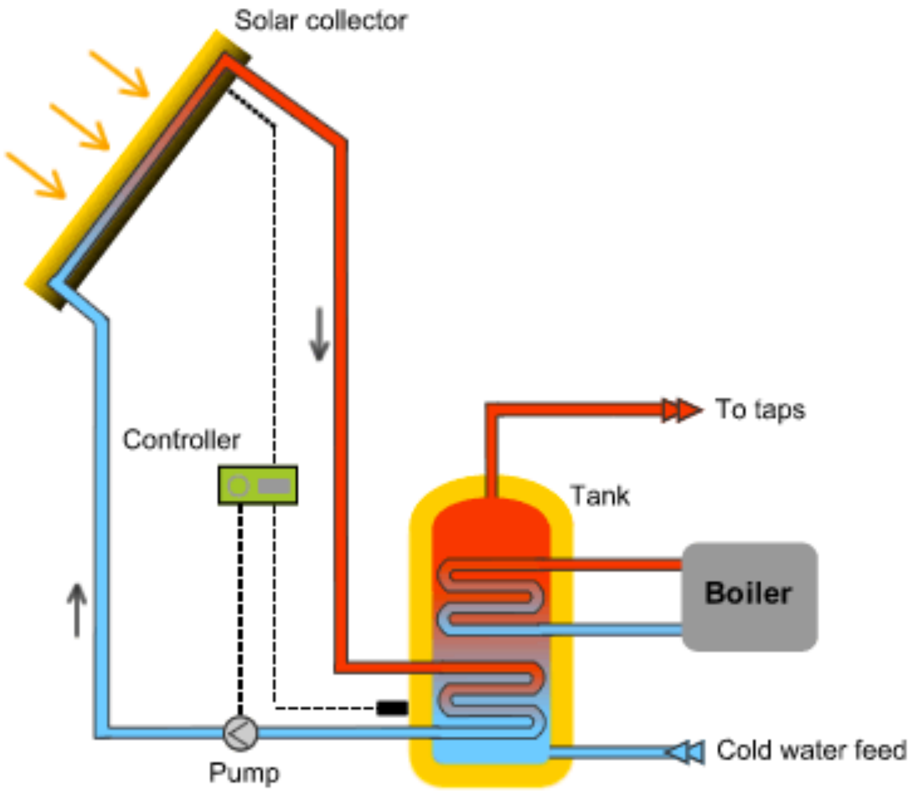


Figure 6: Illustration of a typical solar collector system in a residential building (Andersen I., 2008)

The solar collector is the heart of the solar collector system as it is here the solar radiation is transformed into useful heat. A typical solar collector consists of an absorber, a cover layer and heat insulation. The most important part of the solar collector is the absorber as it is this component that transforms the solar radiation into heat. A heat storage tank is also necessary to be able to store the heat in periods when there is sufficient solar radiation, so that the extra heat can be used in periods when there is not sufficient solar radiation, for instance during night. To distribute the heat to radiators and water heaters it is necessary to connect the solar collector and the storage tank to a distribution system that consists of pipes and pumps. The solar collector system can transfer up to 80 % of the solar radiation into heat (Andersen I., 2008).

Dimensioning of a solar collector system

When installing a solar collector system it is important to analyze the solar potential in the area. How the building is constructed has effect on how well a solar collector system will work. For instance if there are many high buildings around the specified building the solar collectors won't be able to transform the whole solar potential due to shading. However, these conditions cannot be changed for existing buildings, as it is not possible to move the location. It should, though, be considered as a factor when deciding if solar collectors are the proper renovation choice (Andersen I., 2008).

When the solar collector system is designed the location of the solar collector, storage tank and pipelines should be placed so that it is easy to install and maintain the system. The solar collector system should be dimensioned to cover between 40 % and 70 % of the yearly heating demand. It is not economically efficient to dimension the solar collector to cover the entire heating demand since the solar collector are not able to cover the heating demand during winter when the solar radiation is low (Andersen I., 2008).

2.7.2 Photovoltaics (PV-panels)

The most important and relevant solar cell technologies today are crystalline solar cells and thin film technologies. When choosing a solar cell the relationship between price and efficiency is important, as well as accessible surface area. However, the energy that gets transformed to electricity is solar radiation, which is available and free. The efficiency of solar cell is defined as the relation between solar radiation and produced electricity. Since a solar cell is very dependent on the solar radiation to produce electricity it is not sufficient to cover the entire energy need by solar cells. It is however possible to produce more than required during the summer and give the surplus production to the electricity grid, and thereby be able to get some back from the electricity grid during the winter (Ramm, 2014).

The efficiency of the solar cells that are available on the market today is 15 %, and have the ability to supply Norway with 120 TWh every year by covering only 0.4 % of the total land area. This production corresponds to the total electricity production in Norway today. If an efficient solution to store electricity from solar cells is discovered, this technology has the potential to cover Norway's entire need for electricity (Worren & Lohne, 2011).

Compared to other technologies, solar cells are still very expensive. However, the industry is continuously working with researches and new solutions that can lower the cost. Norway is one of the largest solar cell producers and is the leading country when it comes to production of silicon, which is the most common material used in solar cells. NTNU and SINTEF has a world leading environment when it comes to production of silicon for solar cells, and are constantly working to come up with new and more efficient technologies (Worren & Lohne, 2011).

Up until today solar cells have been associated with green energy production, but researches done on the entire life cycle of a solar cell have shown that it may not be as green as first anticipated. Under production of solar panels huge amounts of water is required to get rid of different chemicals etc., and this water again needs to be treated in separate treatment plants to remove the toxic compounds. In addition it is emitted, during production, hexafluoroethane (C2F6), nitrogen trifluoride (NF3), and sulfur hexafluoride (SF6), which are powerful greenhouse gases, with a global warming potential (GWP) of 9 200, 17 200 and 39 800 gram CO_2-eq. respectively. When including these factors in an environmental accounting the solar cell technology don't look that green. This shows the importance of looking at the entire life cycle, and not only on the usage phase. In Germany the overall life cycle emissions from solar cells are calculated to be 180 gram CO_2-eq. per generated kWh electricity (Andersen O., 2013). In this report, however, it is only looked at emissions connected to the usage phase, which makes solar cell technology more environmental friendly.

2.7.3 Building envelope upgrade

Upgrades done on the building envelope involves decreasing the transmission losses and the infiltration losses. In general, buildings built before 1980 have a bad thermal envelope with relatively high U-values (see chapter 3.1.1). Today, the technical regulations require that new buildings satisfy certain requirement (see chapter 2.2), and to be able to fulfill these requirements upgrades have to be done to the building envelope. The main benefit of decreasing the U-value of the building envelope is energy savings. Getting a tighter building envelope also has benefits for the indoor environment since it leads to a more steady temperature inside the building. However, if the building envelope becomes too tight the need for a good ventilation system increase, since natural ventilation through infiltration through walls etc. are decreased significantly (Loga & Diefenbach, 2012).

Windows

Windows in old buildings general have higher U-value than new windows. Changing to windows with lower U-value is therefore beneficial for the building's energy use. However, the effect of improving the window quality is dependent on the total window area of the building as well as the quality of the original window. In this report it is assumed that the windows of old apartment blocks do not have a U-value lower than 2.6 W/m^{2}K (Prognosesenteret AS & Entelligens AS, 2012). For apartment blocks built before 1956 it is natural to believe that the U-value of the original buildings actually was lower. However, since bad window quality has a huge impact on the thermal comfort inside the building it is assumed that almost all buildings have upgraded their windows so that the average U-value for these buildings today varies from 2 to 2.6 W/m^{2}K (Prognosesenteret AS & Entelligens AS, 2012).

The technical regulations today require a U-value for windows below 1.2 W/m^{2}K (Kommunal- og regionaldepartementet, 2010). By 2015 the passive house standard can be set as the technical requirement, which gives a stricter requirement for windows with a U-value below 0.8 W/m^{2}K (NS3700, 2013). A good window is recognized as a window that let in most of the solar radiation that leads to a lower heating demand, emit minimal heat, reflect solar radiation that lead to overheating, is draft-free and provide good thermal comfort inside the building. Table 5 shows different window-types that exist on the marked today. Generally, Enova recommends a U-value below 1 W/m^{2}K (Enova b, 2012).

Table 5: Guiding U-values for different window types (Enova b, 2012)

Window information	U-value (W/m^{2}K)
Single glazed frame	5.0
Connected window with two layer of glasses	2.4
Double glazed Insulating Glass	2.4
Double glazed Insulating Glass with one coated glass and air	1.6
Double glazed Insulating Glass with one coated glass and argon gas	1.4
Double glazed Insulating Glass with coated glass, argon gas, warm edge and new frame	1.2-1.1
Three layers of Insulating Glass with two coated glass, argon gas, warm edge and new frame	1.1-0.9
Three layers of Insulating Glass with two coated glass, argon gas, warm edge and insulated frame	0.9-0.7

By changing to modern windows it is possible to eliminate cold drafts completely, which increase the comfort level considerably. This comfort level is achieved best when choosing three-layer low-energy windows (Enova b, 2012).

Extra insulation in external walls, floor and roof

For old buildings it is common to improve the building envelope by adding additional insulation in external walls, floor and roof. The most common materials used for this are mineral wool and expanded polystyrene (EPS). The last material, EPS, is the most common plastic foam insulation used in building. EPS have excellent insulation properties, low moisture absorption and high comprehensive strength (EPS-gruppen, 2008). However, mineral wool is the most used insulation type and in this report it is decided to use this material when adding additional insulation to the building envelope as it has the lowest thermal conductivity value (0.037 W/mK) (Bøhn & Ulriksen, 2006). Mineral wool is the generic term for glass wool and rock wool. WHO has classified mineral wool as part of group 3, which implies that the material does not increase the cancer risk for humans (Norima, 2010).

Adding additional insulation to external walls can be done by either implementing exterior supplementary insulation or interior supplementary insulation. One of the benefits of adding supplementary insulation to the outside of the walls is that it is possible to live in the dwelling while refurbishments are done. Other benefits are that the utility floor area is not reduced, and the thermal bridges are often removed as a consequence of the refurbishment. Adding additional insulation to the outside of the walls also gives less risk of condensation of interior surfaces and therefore less risk of mold and fungal growth. The disadvantage of adding exterior supplementary insulation to the walls is that it is a comprehensive measure and should be viewed in the context of the need for renovation. Another disadvantage is that the windows have to be moved out of the walls in order to keep the original appearance of window frames. It can also be difficult to maintain "valuable" facades, windows and architectural details (Enova a, 2012).

The benefits of adding supplementary insulation at the inside of the external walls are that there are no changes to the façade, the insulation work can be performed for only parts of the dwelling, and the supplementary insulation can be limited to the coldest room of the dwelling. The disadvantages with this refurbishment technique are that the utility floor area gets reduced, internal refurbishment may be needed since existing slabs and panels must be removed or rebuilt, installations against outer walls must be moved, thermal bridges are often intact after refurbishment, and it can be difficult to install a tight vapor barrier (Enova a, 2012).

Enova generally recommends implementation of supplementary insulation at the outside of the exterior walls (Enova a, 2012). To upgrade a building to passive house standard it is almost always necessary to insulate at the outside of the exterior walls. It is natural to focus on energy-efficient solutions and comfort rise when refurbishment techniques of existing dwellings are chosen. It is often not necessary to satisfy all criteria in TEK10, but choose the measures that lead to a net saving potential economically. It will later be discussed whether a TEK10 or a passive house upgrade will be realistically possible to achieve (Prognosesenteret AS & Entelligens AS, 2012).

2.7.4 Air-to-air heat pumps

An air-to-air heat pump use heat from the ambient air to heat the air inside the dwelling. An air-to-air heat pump general works like a reversed refrigerator as it removes heat from the ambient air, so that the ambient air gets colder while the room temperature increase. The efficiency of an air-to-air heat pump generally is around 3. That means that per added unit of electricity the heat pump will produce 3 times as much heat (Slørdahl, 2013).

A downside by using an air-to-air heat pump is that the efficiency decrease when the outside temperature decrease. However, the heat pump can give heating effect at temperatures down to -10-15 °C. But, since the efficiency is lower than optimal at the coldest days of the year it is not possible to use an air-to-air heat pump as the only heating option. It is normal to use an electric radiator to cover the peak loads. An air-to-air pump is not able to cover the domestic hot water heat demand. It is though possible to install an air-to-water heat pump that can cover this heating demand, and one of the renovation packages analyzed in this project includes this (Slørdahl, 2013).

The cost of installing an air-to-air heat pump is between 17 000 and 35 000 NOK depending on the heat pump capacity. The lifetime of the pump is between 10 and 15 years. In buildings without a waterborne heating system, installation of air-to-air heat pumps is considered the cheapest option. The benefit by using heat pumps is that it is possible to use them as a cooling unit when there is need for cooling (Slørdahl, 2013).

Generally an air-to-air heat pump is best suited for buildings with a total energy use higher than 15 000 kWh per year. The cost of installing an air-to-air heat pump is moderate compared to the energy savings. A heat pump does also gives a steady heat, which gives a good indoor environment. A disadvantage is that the heat pump is very dependent on an open floor plan to be able to distribute the heat in a good way (Enova & Miljødirektoratet, 2013).

2.7.5 Balanced ventilation system with heat recovery

A good ventilation system should give a good indoor environment, limit the indoor humidity, while at the same time be energy efficient. A balanced ventilation system with heat recovery qualifies all these requirements. The heat from the exhaust air is transferred to the fresh inlet air by a heat exchanger, and the air is transported into the building through channels and valves (ENOVA hjemme, 2013).

Buildings generally have three options when it comes to choosing a ventilation system. A natural ventilation system does not use fans or other electrical equipment to transfer the air through the building, but only natural forces like wind and temperature difference between outdoor and indoor temperature. This sort of ventilation system was the dominant one in dwellings built before 1970, and since it does not require a channel-system in the building it is very cheap to install. However, it can be difficult to get satisfying air quality in the building with this ventilation form, and it is often necessary to open windows and doors to get the desired indoor air quality. It is also not possible to recover the heat in the exhaust air when using this ventilation form. Mechanical ventilation is similar to natural ventilation, except that mechanical ventilation uses fans to regulate the airflow. The benefit of using mechanical ventilation is that it is possible to control the airflow without increasing the investment cost considerably. However, it is not possible to recover the heat from the exhaust air. The last ventilation system is a balanced ventilation system with heat recovery, and this is the most common ventilation form in new buildings. Depending on the efficiency of the heat exchanger it is possible to recover between 60 % and 90 % of the heat in the exhaust air. By doing this it is not necessary to use electricity to heat the inlet air (ENOVA hjemme, 2013).

When deciding where to place the ventilation unit it should be placed in a way that makes it easy to perform maintenance work. It is also beneficial to place it close to supply and exhaust valves so that the air doesn't have to move a long way through the channels before entering the ventilation unit. Figure 7 shows an example of how the channels and ventilation unit can be placed in a detached house (ENOVA hjemme, 2013).

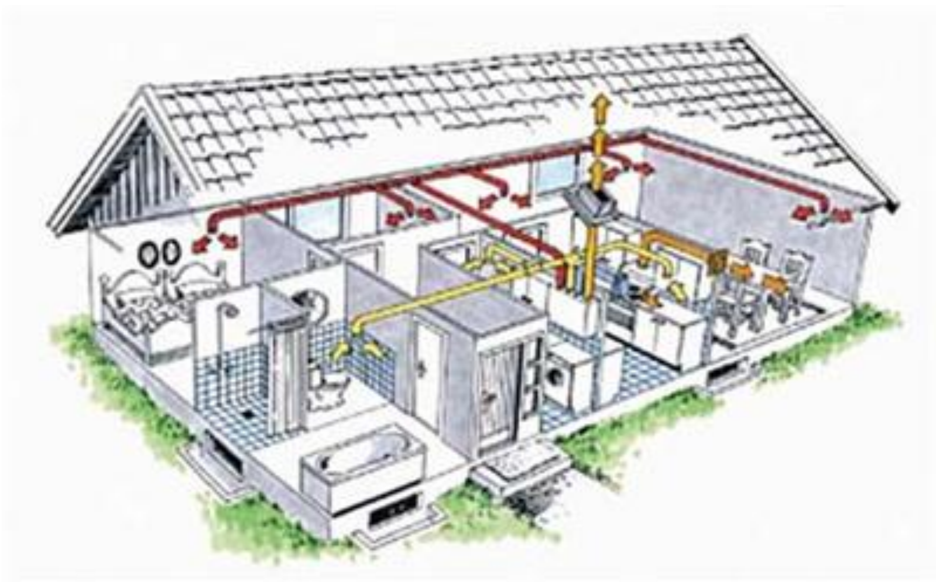


Figure 7: Balanced ventilation system in a detached house (ENOVA hjemme, 2013)

Since kitchen, bathroom and laundry room should have a separate fan that leads the exhaust air directly out without entering the heat exchanger it is beneficial if the building is constructed in a way that makes these three units close to each other. However, in exiting buildings it is not possible to change the placement of these rooms, so the ventilation system may therefore not be optimal (ENOVA hjemme, 2013).

Using a balanced ventilation system gives several benefits. For instance, it is possible to recover the heat from the exhaust air, and therefore save electricity. A system like this also gives a comfortable indoor climate, as it makes sure that the air change is sufficient. It is also possible to regulate the airflow depending on the need for fresh air, and at the same time make sure that the inlet air is free from particles. A sufficient air change rate also makes sure that a possible radon concentration is decreased as much as possible (ENOVA hjemme, 2013)

The disadvantage of using a ventilation system like this is that it requires some electricity to control the ventilation unit. It also has an increased need for maintenance compared to a natural ventilation system, as the filters have to be changed regular. The installation costs are also much higher, and it can be complicated to install the required channel system in existing buildings. However, based on calculations done by Byggforsk it possible to reduce the energy loss from the ventilation system by 75 % by installing a balanced ventilation system. Especially in passive houses it will contribute to reduce a big part of total heat loss, as most of the heat losses are connected to the ventilation system since the transmission losses are small due to a tight building envelope (ENOVA hjemme, 2013).

The government requires a minimum ventilation rate of 0.5 air exchange per hour when it is in use and 0.3 air exchange per hour when it is not in use. A balanced ventilation system can normally switch between low, normal and high airflow rate, which corresponds to 0.3, 0.5 and 0.75 air exchange per hour respectively. It is beneficial that the exhaust airflow rate is 5-10 % higher than the inlet airflow rate to prevent moisture intrusion into the building structure (ENOVA hjemme, 2013).

2.7.6 Water-based heating system

A water-based heating system is a heating system that uses water as an energy carrier. There are general two ways of installing a water-based heating system, through radiators or underfloor heating. The water is transferred through the building in pipes, one for the hot water and one for the cold return water. The cold water is heated by an external heat source, and since water can be heated by several heat sources the flexibility of the system is good (Haarberg, Hansen, Bjørneng, & Vasvik, 2012).

Studies have shown that water-based heating systems are relatively expensive in Norway compared to other countries, like Sweden, and the costs can differ considerably from project to project. The reasons for these differences can be explained by lack of competence, lack of competition, adverse Business Sector structures etc. (Haarberg, Elnan , & Essen , 2010). One of the reasons why it is more expensive to install water-based heating system in Norway is because of high salary costs and less financial maturity. Due to low electricity prices in Norway, direct electricity has been the major heating source up until now. In Sweden, on the other hand, district heating has been one of the dominant heating sources since it was established in 1940 (Svensk Fjärrvärme, 2009). Since Sweden have longer experience with installation of water-based heating systems in buildings and have a more systematic way of installing these systems, the investment cost gets lower (Haarberg, Elnan , & Essen , 2010).

In some buildings it can be beneficial to combine radiators and underfloor heating, for instance by having underfloor heating in bathrooms, bedroom etc., and radiators in living room, kitchen etc. By combining these two systems it is possible to get the benefits from both systems. Radiation heat from radiators provides a warm and comfortable experience. In areas where the user wish to experience a higher temperature it can be beneficial to use underfloor heating as this can reduce the energy need as the experienced temperature in the room feels higher than it actual is (Haarberg, Elnan , & Essen , 2010).

Some of the costs related to installing a water-based heating system is due to transportation of components. The plumber have a starting price of 2000 NOK before any work is done. However, these costs are often enrolled into the hourly price. In the Norwegian HVAC market about 10 % of the total installation cost goes to engineering and subcontracting, 40 % goes to material costs and 50 % is related to labor. As seen by this division a big part of the costs are related to material use, which is much higher in Norway than in Sweden. In Sweden the labor costs stand for approximately 70-90 % of the total installation costs, while the material costs contributes to 10-30 %. To hire a plumber the consumer must general pay between 595 NOK and 660 NOK per hour to cover all the expenses related to work, administration, materials etc. (Haarberg, Elnan , & Essen , 2010).

As mentioned earlier the majority of buildings in Norway use direct electricity for both space heating and domestic hot water. This has led to a slow development in knowledge and experience around constructing buildings with a water-based heating system, hence giving a higher installation cost. But it is anticipated that the investment cost will decrease in the future when the Norwegian competence on the field increase (Haarberg, Elnan , & Essen , 2010).

2.7.7 District heating

A district heating system consists of one or more heating centrals that produce and deliver heat, a heat distribution grid and a subscription central. In the distribution grid there are two pipes, one for hot water and one for cold water. The hot water coming from the heating central will normally have a temperature between 80 °C and 120 °C. The water going back to the heating central will normally have a temperature between 40 °C and 75 °C (Utne, 2012). Preferably the differences in temperature between the two pipes should be as high as possible. The benefit of using district heating is that heat can be produced efficiently in production centrals several miles from where the heat is consumed. Since the water transported from the heating central often has high temperature and pressure (up to 120 °C and 16 bar) the pipelines must provide good insulation. For safety reasons and to avoid high pressure and temperatures inside the buildings, it is preferable that each house has its own waterborne system that is hydraulically separated from the external one. This is done by a heat exchanger installed in each house (Rosvold, 2011).

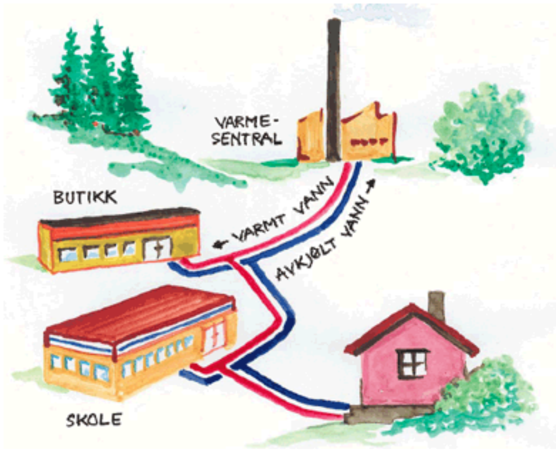


Figure 8: District heating illustration

The heating source in a district heating network is often waste, which makes it an environmental friendly heating choice. To cover peak loads other sources with low investment cost are used, like oil, gas, electricity etc. In Norway there is also an Energy Act that requires that all buildings built in a concession area for district heating should be built with a waterborne heating system so that they can be connected to the district heating grid. District heating is not very big in Norway compared to Denmark and Sweden. However, in Trondheim and some areas of Oslo the network is well developed. In Trondheim over 30 % of the total heating demand is covered by district heating (Rosvold, 2011).

General the district heating companies can require a payment that is similar to the electricity price. However, the price of district heating should be a bit lower than electricity to make it competitive. It is normal to pay about 90 % of the electricity price for district heating, and this is the price that is used in this project (Econ, 2010).

2.8 Support schemes from Enova

Enova have several support schemes to promote energy efficiency measures in existing buildings. Investment support is given to physical measures that can reduce the total energy use in buildings and that contribute to an increased use of renewable energy sources. The support amount is automatically calculated for the different measures based on the incremental cost of the measures (Enova c, 2014).

The meaning with the Enova program is to promote the best available energy technologies and solutions, and increase the use of renewable energy solutions. Energy efficiency projects that are not supported by Enova are installation of air-to-air heat pumps and installation of heating plants for buildings that are obligated to connect to the district heating grid (Enova c, 2014).

The funding level is calculated in the application and reporting center based on what kind of measure it is and the amount of measures that is planed to be performed. Enova gives support to three different kinds of measure categories (Enova c, 2014). These are:

- Energy reducing single measures
- Heating plants and conversion to waterborne heating
- Upgrading to passive or low energy standard

Generally, applications with low required support per kWh is prioritized above applications with high support per kWh. To receive support from Enova it is necessary that the support is crucial for the implementation of the energy efficiency measure and it is important to send in an application to Enova before the renovation project is started (Enova c, 2014).

Enova can give up to 20 % of the additional costs for upgrading a building to passive house level (Enova c, 2014). There is no maximum support amount for bigger apartment blocks and commercial buildings, but for the calculations it is assumed that it is not possible to get more than 200 000 NOK per measure, due to the fact that the maximum support amount for solar collectors are 200 000 NOK. The support rate per m^2 solar cell area is 201 NOK. For installation of air-to-water heat pumps the support rate is set to be 1 100 NOK/kW for existing buildings (Enova e, 2014).

Since it is difficult to calculate exact support amount from Enova, it is assumed that each of the measures in this report that are qualified for support can get 20 % of the investment cost up to 200 000 NOK in support.

2.9 EPISCOPE/TABULA

TABULA stands for Typology Approach for Building Stock Energy Assessment and aims to create a harmonized structure for European building typologies.

EPISCOPE stands for Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks and aims to make the energy refurbishment processes in the European housing sector more transparent and effective with the aim to ensure that the climate protection targets will be attained and that corrective or enhancement actions can be taken in due time, if necessary (Build up, 2013).

"The purpose of the TABULA data structure is to facilitate the understanding of typical buildings, supply systems and refurbishment measures in the different European countries and to lay the basis for scenario calculations on a supranational level. It is not the intention to adapt this Excel workbook to national regulations. For your national calculations you will generally use your own tools and publish the building system datasets with respect to your national standards." (Loga, 2012).

2.9.1 Methods for classification of building typologies

Denmark and Sweden have already developed their own TABULA model and defined their own building typologies. Denmark has decided to divide the residential building stock into single-family houses, terraced houses and apartment blocks, while Sweden has decided to divide the building stock into single-family houses and multi-family houses. Denmark has also divided the building stock into 9 construction periods, where each construction period represents a period where the building technique and isolation level was approximately the same (Wittchen & Kragh, 2012).

In Norway it is decided to follow many of the same principles as Denmark since the construction technique throughout time is very similar. It is decided to divide the Norwegian dwelling stock into detached houses and multi-family houses/ apartment blocks. The time-periods are chosen based on when the changes in building technique were made. As mentioned earlier only the three first time periods are analyzed in this project, hence apartment blocks built before 1956, between 1956 and 1970, and between 1971 and 1980 (Prognosesenteret AS & Entelligens AS, 2012).

2.10 Analysis methods and results from similar studies

2.10.1 Energy balance model/material flow analysis (MFA)

The model used to calculate the energy flows in this project is an energy balance model based on the principle of material flow analyses (MFA). MFA is a method used to quantify flows and stocks within a system defined in space and time. It is based on the law of the conservation of matter and that makes it simple to control the material/energy balance by comparing all inputs, stocks, and output of a process. When performing an MFA it is important to define proper system boundaries. The system may be a process, industry or region of concern. By making a flow chart with clear system boundaries and well-defined flows and stocks it is possible to graphically allocate the meaning of measurements or statistical data (Brunner & Rechberger, 2004). This is what is done in this project. The energy balance model is based on the TABULA calculation method and all the flows in the system are calculated based on equations given by TABULA (Loga & Diefenbach, 2012).

Since the model is based on energy flows and not material flows it cannot be defined as an MFA. However, an energy balance analysis uses the principles of an MFA and the MFA methodology is therefore of great concern. MFA is an appropriate tool to investigate the flows and stocks of any material-based system. When developing an MFA-model the following steps should be followed (Brunner & Rechberger, 2004):

1. Delineate a system of material flows and stocks by well-defined, uniform terms. In this project the building's space heating system is defined as one system and the building's domestic hot water (DHW) system is defined as another (see Figure 9)
2. Reduce the complexity of the system as far as possible while still guaranteeing a basis for sound decision making. The energy balance model is divided into one model for the space heating system and one model for the domestic hot water system to reduce the complexity of the system as far as possible. However, some of the outflows from the domestic hot water system is linked to the space heating system, so it can be discussed whether two separate systems are preferable in this case.
3. Assess the relevant flows and stocks in quantitative terms, thereby applying the balance principle and revealing sensitivities and uncertainties. Many of the flows in the report are calculated based on equations given in TABULA and are called model approach equations (see Table 11). To maintain a balance of input- and output flows several energy balance equations are necessary, and these are defined in Table 10.
4. Present the result as a basis for managing resources, the environment and wastes. In this case the results show the energy saving potential by implementing several refurbishment technologies. The environment will be affected by the energy use in buildings since the energy source often is electricity. The global warming factor for electricity in Norway is very low though since almost all electricity is based on hydropower. However, since this is not the case for the rest of the world it is better to use an average value for Europe (NS-EN 15603, 2008).

2.10.2 NS3031 – Calculation of energy performance of buildings

NS3031 is the Norwegian standard for calculation of energy performance of buildings. The standard describes the method used and common standardized data for different parameters. The input data that is required for the energy calculations are divided into standardized values, approximate values, and documented values. The standardized values includes locked values for operating hours, internal loads, indoor temperature and climate. These values are used when comparing to governmental energy requirements (NS3031, 2011).

NS3031 gives three different calculation methods for estimation of the heating- and cooling demand in buildings, where one is a monthly calculation method (stationary method) that uses the principles of NS-EN ISO 13790, one is a simplified hourly calculation method (dynamic method) that uses the principles given in NS-EN ISO 13790, while the last one uses detailed validated simulation programs (dynamic method) based on the principles in NS-EN 15265 (NS3031, 2011). In this study a stationary energy calculation method is used that uses the principles given by TABULA. Many of the calculation principles given in TABULA are though similar to the stationary calculation method described in NS3031, and many of the standardized values given in this standard are used in the energy calculations done in this project.

The standard gives a detailed description of the calculation method, but this method is not described thoroughly in this report since it is the TABULA methodology that is used to calculate the energy use for space heating and domestic hot water. This method is though, as mentioned over, quite similar to the method given in NS3031, but somewhat simplified.

In this Master thesis standardized values are used for domestic hot water, internal loads, ventilation air rates etc., and these values can be found in Table 6 (NS3031, 2011).

Table 6: Standardized data for heating demand and internal heat loads (NS3031, 2011)

	Domestic hot water demand		Internal loads from lighting		Internal loads from electrical equipment		Internal loads from persons		Minimum specific air rate
	W/m^2	kWh/m^2year	W/m^2	kWh/m^2year	W/m^2	kWh/m^2year	W/m^2	kWh/m^2year	$\frac{m^3}{h \cdot m^2}$
Apartment block	5.1	29.8	1.95	11.4	1.8	10.5	1.5	13.1	1.2

See NS3031 for more information of dynamic calculation methods and other parameter values.

2.10.3 Energy use in buildings – literature study

Enova has undergone a detailed study when it comes to energy use in Norwegian dwellings before and after a TEK10 renovation. Since the same building types used in this report is used in the Enova report it is especially interesting to compare the energy results from these two studies. For the standard apartment built before 1956 Enova has estimated a typical energy demand of 217.9 kWh//m^{2}year. This includes energy need to space heating, domestic hot water, electrical equipment and lighting. For the standard apartment built between 1956 and 1970 the estimated energy use is estimated to be 197.9 kWh/m^2. This implies an energy improvement of 20 kWh/m^2 from the first period to the second, mainly because of reduced energy use to space heating. The standard apartment built between 1971 and 1980 have an estimated net energy use of 114.3 kWh/m^2, which implies a major improvement from the previously standard types (Prognosesenteret AS & Entelligens AS, 2012).

By using these standard dwelling types an estimated total amount of delivered energy to apartment blocks built before 1956 is set to be 2.61 TWh in 2010. Statistic Norway estimated the same year that the total energy delivered to apartments built before 1956 should be 2.03 TWh. This gives an error of 29 %, which shows that using standardized building types is not completely compatible with the reality. For the two first periods Enova general estimates higher delivered energy demand than what is registered by Statistic Norway, but for the third time period (apartments built between 1971 and 1980) the calculated delivered energy amount from Enova is lower than what is registered by Statistic Norway. Enova estimates a delivered energy amount of 0.79 TWh, while Statistic Norway registers a total amount of delivered energy of 1.06 TWh for apartments built between 1971 and 1980. However, the overall error for all apartments built before 2010 is only estimated to be 4 %, which results in a pretty small error when looking at the total energy use for the entire dwelling stock (Prognosesenteret AS & Entelligens AS, 2012).

Enova has calculated a total technical energy saving potential when upgrading apartment blocks built before 1980 to TEK10 standard of 1.72 TWh. Upgrading the total Norwegian dwelling stock to TEK10- level is calculated to give a technical energy saving potential of 13.4 TWh, which corresponds to a 30 % energy reduction (Prognosesenteret AS & Entelligens AS, 2012).

Studies done by SINTEF show that it is possible to save 12 TWh by the end of 2020 by implementing energy efficiency measures in existing buildings. Approximately 10 of these 12 TWh comes from decreased electricity use. This reduction in energy use is estimated to give a saving potential of 80 billion Norwegian kroner. If the saved energy from the building sector is used to electrify the transport sector and the offshore operations as well as eliminate all oil heating, it is possible to reduce the Norwegian climate gas emissions by 6 million tons. This reduction corresponds to approximately 40 % of the national climate gas reduction goal for 2020 (Dokka, Hauge, Thyholt, Klinski, & Kirkhus, 2009).

Studies done in Poland shows that the energy intensity is the main source for negative impact. Traditional buildings are calculated to have 3.6 times higher energy consumption than passive houses, which gives strong incentives for a passive house upgrade of existing buildings (Pajcheowski, Noskowiak, Lewandowska, & Strykowski, 2013).

2.10.4 Life Cycle Costing (LCC) of energy rehabilitation in buildings.

Research done by the KRD's working group for energy efficiency in buildings show that the extra cost connected to upgrading an existing building to passive house level lies between 500 NOK/m^2 and 2500 NOK/m^2. Assuming that 15 % of the existing buildings in the period between 2010 and 2015 are upgraded to passive house level, and that this amount gradually increase to 75 % from 2015 to 2050, the aggregated extra costs in the period 2010-2015 is estimated to be 1 555 million NOK per year, while the aggregated extra costs in the period 2015-2050 is estimated to be 5 829 million NOK per year. (Arnstad, 2010).

Asplan Viak have completed a very similar life cycle costing analysis of different renovation measures to what is done in this Master Thesis, and the results from this study is therefore of great interest. The research done by Asplan Viak is however on component level, but a net present value method is used to calculate the profitability of the measures. The lifetime used by Asplan Viak is approximately the same as the lifetime used in this thesis. Costs connected to window upgrading is evaluated to give a profit during a period of 30 years between 112 NOK/m^2 and 990 NOK/m^2 for building in original state when using a discount rate of 4 % (Førland-Larsen, 2012). Upgrading the windows to passive house level is therefore seen as a profitable measure.

Since the building types used in the Asplan Viak report is the same as the building types used in this Master Thesis the results are directly comparable. Upgrading the exterior walls of a typical apartment block built before 1956 in original state to TEK10 level is estimated to cost 392 NOK/m^2 heated floor area and give a profitability over a period of 30 years of 684 NOK/m^2 heated floor area when using a discount rate of 4 % and an electricity price of 1.0 NOK/kWh (Førland-Larsen, 2012). Table 7, Table 8 and Table 9 shows the results calculated by Asplan Viak for a TEK10-upgrade of the building envelope for all relevant building types. The net present value here is calculated by using energy savings instead of energy costs, which implies that a positive net present value gives a profitable measure, while a negative net present value gives an unprofitable measure. All the net present values are calculated using a discount rate of 4 % and an energy price of 1 NOK/kWh (Førland-Larsen, 2012).

Table 7: NPV-results from Asplan Viak study – TEK10 upgrade of the exterior walls (Førland-Larsen, 2012)

	Apartments built before 1956		Apartments built between 1956 and 1970		Apartments built between 1971 and 1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
Investment cost (NOK/m^2 BRA)	392	336	354	252	149	No change
NPV (NOK/m^2 BRA)	684	32	906	-90	-7	-

Upgrading the exterior walls to TEK10 level is most beneficial for the building types with highest energy use before renovation. For apartments built in the period 1956-1970 in historical refurbished state and apartments in original state from the period 1971-1980 upgrades of the exterior walls are calculated to not be profitable over a period of 30 years (Førland-Larsen, 2012).

TEK10 upgrades are done for roof and floor as well, and the results from the study are given in Table 8 and Table 9.

Table 8: NPV-results from Asplan Viak study – TEK10 upgrade of roof (Førland-Larsen, 2012)

	Apartments built before 1956		Apartments built between 1956 and 1970		Apartments built between 1971 and 1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
Investment cost (NOK/m^2 BRA)	54	36	-	-	-	-
NPV (NOK/m^2 BRA)	296	19	-	-	-	-

Table 9: NPV-results from Asplan Viak study – TEK10 upgrade of floor (Førland-Larsen, 2012)

	Apartments built before 1956		Apartments built between 1956 and 1970		Apartments built between 1971 and 1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
Investment cost (NOK/m^2 BRA)	89	61	61	Not calculated	Not calculated	Not calculated
NPV (NOK/m^2 BRA)	62	7	-5			

As seen from the tables the results from the Asplan Viak report are lacking some information when it comes to upgrades of floors and ceilings. But the results general show that it is beneficial to insulate roof and floors for apartment blocks built before 1956. The better the original value of the envelope elements are the less profitable these measures gets (Førland-Larsen, 2012).

Other studies show that investing in control systems for energy, sealing windows and doors, installing air-to-air heat pumps, and replacing old wood stoves are seen as the most profitable energy efficiency measures. For old buildings with high heating requirements before renovation it is also seen very profitable to upgrade the building envelope (Ibenholt & Fiksen, 2011)

3 Methodology

3.1 Methods, variables and equations for energy calculations

All calculations done in this project are based on the method used in TABULA, and the same equations are used. Figure 9 describes the idea behind the following equations. It is focused on the energy use for space heating and domestic hot water. Cooling, air conditioning, lighting, and electric appliances are not considered, but may be of great interest at a later stage.

The method used for the calculation is the predefined TABULA method, which requires several input factors, which will be thoroughly examined in this chapter. The TABULA calculations are based on the method described in EN ISO 13790 on the basis of a one-zone model (Loga & Diefenbach, 2012). The model uses the principle of MFA, and is developed as an energy balance model that uses the MFA methodology.

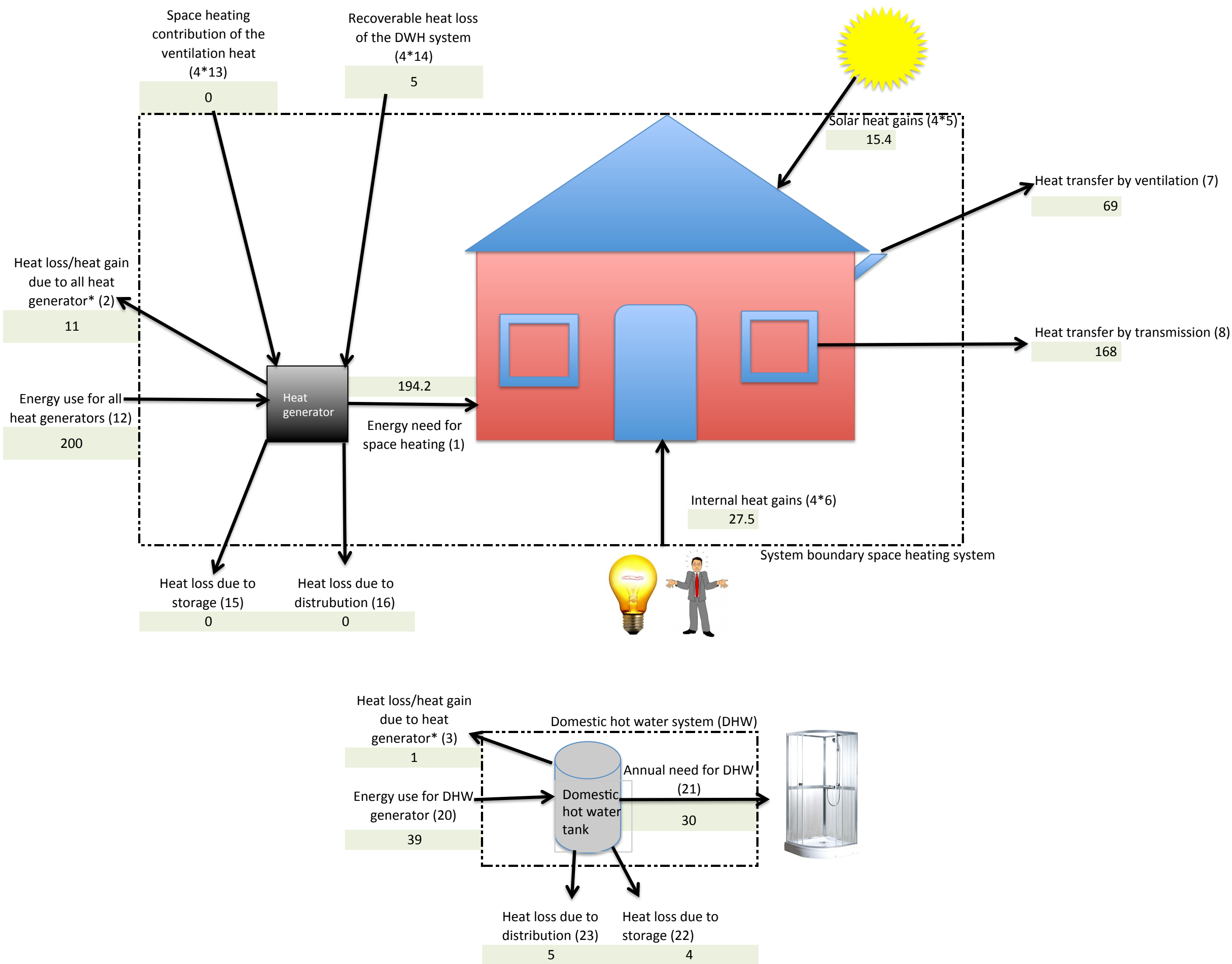


Figure 9: Energy balance flow chart (based on MFA-methodology)

All values in Figure 9 are given in kWh/m^{2}year. The number in parentheses behind the text for each flow is the relevant equation number that can be found in either Table 10 or Table

11. Some of the parentheses involve a multiplied number. This implies that the flow is found as the product of these two equations.

The flow values shown in the figure are the energy flows for a typical apartment block built before 1956 in Oslo climate which is set as the reference climate due to Norwegian standard (NS3031, 2011). To calculate the different energy posts in each of the defined building typologies the following 23 equations are used, where three of them are energy balance equations and 20 are model approach equations (see chapter 2.10.1 for description of MFA-modeling).

Table 10: Energy balance equations (Loga & Diefenbach, 2012)

Equation number	Unknown variable name	Equation	Units	Description	Equation number in TABULA
1	$Q_{H,nd}$	$= Q_{ht,ve} + Q_{ht,tr} - n_{h,gn} \cdot (Q_{sol} + Q_{int})$	$kWh/year$	The buildings energy need for space heating	Combination of equation 1,2 and 8
2	$Q_{g,h}$	$= Q_{del,h} + n_{h,gn} \cdot (Q_{ve,h,rec} + Q_{w,h}) - Q_{H,nd} - Q_{s,h} - Q_{d,h}$	$kWh/year$	Heat loss/heat gain due to heat generator of the space heating system	Based on energy balance of the heat generator
3	$Q_{g,w}$	$= Q_{del,w} - Q_{nd,w} - Q_{s,w} - Q_{d,w}$	$kWh/year$	Heat loss/heat gain due to heat generators of DHW system	Based on energy balance of the DHW system

The following equations given in Table 11 are the model approach equations and these equations contain given or calculated parameters that are defined in "key variables" at page VIII. Many of the parameters are building dependent and are different for each building typology.

Table 11: Model approach equations (Loga & Diefenbach, 2012)

Equation number	Unknown variable name	Equation	Units	Description	Equation number in TABULA
4	$\eta_{h,gn}$	$= \frac{1 - \gamma^{a_H}}{1 - \gamma^{(a_H + 1)}}$	-	Gain utilization factor for heating	11
5	Q_{sol}	$= F_{sh} \cdot (1 - F_F) \cdot F\_W \cdot g_{gl,n} \cdot (A_{window,hor} \cdot I_{sol,hor} + A_{window,east} \cdot I_{sol,east} + A_{window,west} \cdot I_{sol,west} + A_{window,north} \cdot I_{sol,north} + A_{window,south} \cdot I_{sol,south})$	$kWh/year$	Solar heat load during the heating season	10
6	Q_{int}	$= t_{døgn} \cdot \varphi_{int} \cdot d_{hs} \cdot A_{C,ref}$	$kWh/year$	Internal heat gains during heating season	9
7	$Q_{ht,ve}$	$= t_{døgn} \cdot H_{ve} \cdot F_{nu} \cdot (\vartheta_{int} - \vartheta_e) \cdot d_{hs}$	$kWh/year$	Heat transfer by ventilation during heating season	6
8	$Q_{ht,tr}$	$= t_{døgn} \cdot H_{tr} \cdot F_{nu} \cdot (\vartheta_{int} - \vartheta_e) \cdot d_{hs}$	$kWh/year$	Heat transfer by transmission during heating season	3
9	$Q_{del,h,1}$	$= \alpha_{nd,h,1} \cdot e_{g,h,1} \cdot (Q_{H,nd} - \eta_{h,gn} \cdot (Q_{w,h} + Q_{ve,h,rec}) + Q_{d,h} + Q_{s,h})$	$kWh/year$	Energy use for heat generator 1 of the heating system	19 and 20

10	$Q_{del,h,2}$	$= \alpha_{nd,h,2} \cdot e_{g,h,2} \cdot (Q_{H,nd} - \eta_{h,gn} \cdot (Q_{w,h} + Q_{ve,h,rec}) + Q_{d,h} + Q_{s,h})$	$kWh/year$	Energy use for heat generator 2 of the heating system	19 and 20
11	$Q_{del,h,3}$	$= \alpha_{nd,h,3} \cdot e_{g,h,3} \cdot (Q_{H,nd} - \eta_{h,gn} \cdot (Q_{w,h} + Q_{ve,h,rec}) + Q_{d,h} + Q_{s,h})$	$kWh/year$	Energy use for heat generator 3 of the heating system	19 and 20
12	$Q_{del,h}$	$= Q_{del,h,1} + Q_{del,h,2} + Q_{del,h,3}$	$kWh/year$	Energy use for all the heat generators of the heating system	
13	$Q_{ve,h,rec}$	$= \eta_{ve,rec} \cdot Q_{ht,ve}$	$kWh/year$	The space heating contribution of the ventilation heat recovery	21
14	$Q_{w,h}$	$= (q_{g,w,h} + q_{s,w,h} + q_{d,w,h}) \cdot A_{C,ref}$	$kWh/year$	Recoverable heat loss of the domestic hot water system	18
15	$Q_{s,h}$	$= q_{s,h} \cdot A_{C,ref}$	$kWh/year$	Annual effective heat loss of the heating system storage	
16	$Q_{d,h}$	$= q_{d,h} \cdot A_{C,ref}$	$kWh/year$	Annual effective heat loss of the space heating distribution system	
17	$Q_{del,w,1}$	$= \alpha_{nd,w,1} \cdot e_{g,w,1} \cdot (Q_{nd,w} + Q_{d,w} + Q_{s,w})$	$kWh/year$	Energy use for domestic hot water heat generator 1	16 and 17
18	$Q_{del,w,2}$	$= \alpha_{nd,w,2} \cdot e_{g,w,2} \cdot (Q_{nd,w} + Q_{d,w} + Q_{s,w})$	$kWh/year$	Energy use for domestic hot water heat generator 2	16 and 17
19	$Q_{del,w,3}$	$= \alpha_{nd,w,3} \cdot e_{g,w,3} \cdot (Q_{nd,w} + Q_{d,w} + Q_{s,w})$	$kWh/year$	Energy use for domestic hot water heat generator 3	16 and 17
20	$Q_{del,w}$	$= Q_{del,w,1} + Q_{del,w,2} + Q_{del,w,3}$	$kWh/year$	Energy use for all the domestic hot water heat generators	
21	$Q_{nd,w}$	$= q_{nd,w} \cdot A_{C,ref}$	$kWh/year$	Annual energy need for domestic hot water	
22	$Q_{s,w}$	$= q_{s,w} \cdot A_{C,ref}$	$kWh/year$	Annual heat loss of the domestic hot water storage	
23	$Q_{d,w}$	$= q_{d,w} \cdot A_{C,ref}$	$kWh/year$	Annual heat loss of the domestic hot water distribution system	

Some of the parameters used in the model approach equations are considered of great importance and will be explained further. To calculate the annual ventilation losses (see equation 7 in Table 11) the parameter H_{ve} is required. This parameter is a calculated parameter and can be found by using the following equation:

Equation 1: Calculation of overall heat transfer coefficient by ventilation

$$H_{ve} = c_{p,air} \cdot (n_{air,use} + n_{air,infiltr.}) \cdot A_{C,ref} \cdot h_{rom,ve,ref} \qquad \text{[W/K]}$$

Where

$c_{p,air}$ is the volume-specific heat capacity of air and is set to be 0.34 Wh/m^2K [Wh/m^2K]

$n_{air,use}$ is average air change rate during heating season, related to the utilization of the building [1/h].

$n_{air,infiltr.}$ is air change by infiltration [1/h]

Values for $n_{air,use}$ and $n_{air,infiltr.}$ for the building typologies analyzed in this project are given in Table 12. These values are based on average values given by TABULA (Loga & Diefenbach, 2012).

To calculate the annual heat losses due to transmission through walls etc. (see equation 8 in Table 11) the parameter H_{tr} is required. This parameter is found by using the following equation:

Equation 2: Calculation of overall heat transfer coefficient by transmission

$$H_{tr} = \sum_i b_{tr,i} \cdot A_{env,i} \cdot U_{eff,i} + \left(\sum_i A_{env,i}\right) \cdot \Delta U_{thr} \qquad \text{[W/K]}$$

where

$b_{tr,i}$ is the adjustment factor soil [-]
$A_{env,i}$ is the area of envelope element, i, where i can be wall, window etc. [m^2]
$U_{eff,i}$ is the effective U-value of element i [W/m^2K]
ΔU_{thr} is the surcharge on all U-values, taking into account the additional losses caused by thermal bridging [W/m^2K]

Information on values for different important parameters is given in the following chapters. More detailed information of all parameters can be found in appendix D1.

3.1.1 Building dependent parameters

Based on information given in chapter 2.4 different building dependent parameters are given for each of the three building typologies. An overview of these parameters can be found in Table 12.

Table 12: Building dependent parameters for each time period (in original and historical refurbished state) (Prognosesenteret AS & Entelligens AS, 2012) (Loga & Diefenbach, 2012)

	Before 1956	1956-1970	1971-1980
General information			
BRA ($A_{C,ref}$)	568	1056	1800
Number of units per block (units)	8	16	24
Length x width ($m \times m$)	15.97×8.87	34.18×7.70	39.79×11.24
Number of floors	4	4	4
Ceiling height (m)	2.8	2.8	2.5
Area values for each construction element (m^2)			
Wall ($A_{env,wall}$)	438.8	771.7	738.6
Floor ($A_{env,floor}$)	142	264	450
Roof ($A_{env,roof}$)	142	264	450
Window ($A_{env,window}$)	113.6	158.4	270
Door ($A_{env,door}$)	4	8	12
Area for different windows orientations (m^2)			
Horizontal ($A_{window,hor}$)	0	0	0
South ($A_{window,south}$)	68.16	95.04	162
West ($A_{window,west}$)	0	0	0
East ($A_{window,east}$)	0	0	0
North ($A_{window,north}$)	45.44	63.36	108
Effective U-value for construction (original building state) (W/m^2K)			
Wall	0.82	0.96	0.34
Floor	0.55	0.38	0.24
Roof	0.81	0.33	0.21
Window	2.6	2.6	2.6
Door	2.5	2.5	2
Thermal bridge value	0.15[1]	0.15[1]	0.1[2]
Effective U-value for construction (historical refurbished building state) (W/m^2K)			
Wall	0.41	0.29	0.18
Floor	0.26	0.18	0.21
Roof	0.31	0.24	0.14
Window	2.0	2.0	1.6
Door	2.0	2.0	1.6

[1] The thermal is set to this value due to concrete ceiling etc. that are penetrating insulation (Loga & Diefenbach, 2012)
[2] The thermal is set to this value due to the assumption of medium effect of constructional thermal bridging (Loga & Diefenbach, 2012)

Thermal bridge value	0.1[3]	0.1[3]	0.1[4]
Indoor climate			
Heated part of the apartment	77%	80%	82%
Unheated part of the apartment	23%	20%	18%
Temperature heated part	22	22	22
Temperature unheated part	15	15	15
Average temperature (ϑ_{int})	20.39	20.6	20.74
Air exchange values (1/h) (original building state)			
Average air change rate related to the utilization of the building ($n_{air,use}$)	0.4	0.4	0.4
Air change by infiltration ($n_{air,infiltr}$)	0.4	0.4	0.2
Air exchange values (1/h) (historical refurbished building state)			
Average air change rate related to the utilization of the building ($n_{air,use}$)	0.4	0.4	0.4
Air change by infiltration ($n_{air,infiltr}$)	0.2[5]	0.2[5]	0.2

Buildings built before 1956 typical have a window area that correspond to 20 % of the utility floor area (BRA), while buildings built during the time period 1956-1970 and 1971-1980 typical have a window area that correspond to 15 % of the utility floor area, hence giving the values in Table 12. Based on qualified assumptions given by Enova it is estimated that 60 % of the window area is oriented on the southern side of the building, while 40 % of the window area is oriented on the northern side of the building. This means that the eastern and western sides of the building are constructed without windows. (Prognosesenteret AS & Entelligens AS, 2012).

Figure 10: Typical apartment block from 50s

The air exchange in a building is a result of ventilation ($n_{air,use}$) and infiltration ($n_{air,infiltr}$). Air exchange trough infiltration is caused by leaks in the building envelope, and is generally

[3] Expected to decrease down to a medium level based on qualified assumptions done by the project team and TABULA (Loga & Diefenbach, 2012)
[4] Expected to remain at a medium level even though parts of the building envelope now satisfy TEK10 (Loga & Diefenbach, 2012)
[5] As a consequence of the refurbishments it is anticipated that the effect of air infiltration goes from high to medium (Loga & Diefenbach, 2012)

high for old apartment blocks. The majority of old apartment blocks (built before 1970) use a natural ventilation system, which means that the ventilation of air happens through thermal buoyancy and wind. A natural ventilation system will have highest effect when the difference between indoor and outdoor temperature is high. When outdoor temperature is high during summer the ventilation rate is low, which often gives a bad indoor climate during parts of the summer. A mechanical ventilation system where fans are used to draw exhaust air out of the building was common in apartment blocks at the 1970s. The fresh air is flowing through valves in the exterior walls. Balanced ventilation systems are most common in modern buildings. A balanced ventilation system uses energy from the warm exhaust air to reheat the cold outdoor air, which gives a good indoor climate as well as a lower energy use for heating (Prognosesenteret AS & Entelligens AS, 2012).

Apartment blocks built before 1956 were typical built with only a wood stove for space heating. Some were also built with a central distribution system where an electric boiler was placed in an unheated basement. However, the majority (60 %) of the buildings were built with a wood stove (Pettersen , Lars, Wigenstad, & Dokka, 2005). Today all buildings that were originally built with a wood stove as the only heating source have also implemented direct electric heaters. For domestic hot water it is assumed that there is a water heater in each apartment that is directly connected to the electricity grid (Ulseth, 2013).

Using direct electric heaters became more and more popular in the 1960s due to decreasing electricity prices. Oil was still a cheap resource, but constructing apartment blocks with a waterborne system was more costly than constructing blocks with direct electric heaters. Approximately 71 % of the apartments were now using direct electricity as their main heating source. The rest were built with oil boilers and a central heating system (Pettersen , Lars, Wigenstad, & Dokka, 2005). The typical buildings analyzed in this report use direct electrical heaters. But in the sensitivity analysis the other type is included to see the effect of having a water-based heating system installed in the buildings before renovation.

In 1973 an oil crisis hit the western world, which led to a 70 % increase in the oil price (Lundberg, 2013). Use of oil boilers in buildings therefore decreased significantly in this period, and existing buildings that already had oil boilers installed changed to electricity boilers. New buildings built after 1970 were mainly constructed with direct electric heaters as this was seen as the cheapest option (Ulseth, 2013). The building regulation of 1969 required that all dwellings that were not connected to a shared central heating plant should be constructed with a pipe so that every apartment had a possibility to install a fireplace. This was done in case of electricity shortage. For these buildings it is expected that 10 % of the heating demand is covered by a wood stove (Bøeng, 2005).

Heat pumps have become more and more popular over the last couple of years, and in 2009 18.5 % of the Norwegian households had installed heat pumps. In comparison only 4 % had heat pumps installed in 2004 (SSB, 2011). For apartment blocks that originally use direct electric heaters it has been popular to replace these heaters with air-to-air heat pumps. This kind of renovation was however not very common before 2000 (Ulseth, 2013).

Table 13 shows the chosen combination of energy sources for the building in original state and in historical refurbished state for each time period analyzed in this report.

Table 13: Amount of different energy sources for each building typology (Pettersen , Lars, Wigenstad, & Dokka, 2005) (Bøeng, 2005)

	Before 1956	1956-1970	1971-1980
Energy source			
Direct electricity to space heating ($\alpha_{nd,h,1}$)	90%	90 %	90%
Direct electricity to DHW ($\alpha_{nd,w,1}$)	100%	100%	100%
Wood Stove ($\alpha_{nd,h,3}$)	10%	10%	10%

To calculate the delivered heat to a given heat generator TABULA use a heat generation expenditure factor. This is basically 1 divided by the efficiency of the heat generator and shows how much useful energy that is required per used unit of heat. An old oil boiler will therefore have a high expenditure factor, while a heat pump will have a low expenditure factor. The expenditure factors for different heat generators used in typical original apartment blocks from each of the time periods are given in Table 14. The expenditure factors for heat pumps are given in Table 15 since this is one of the potential renovation technologies that is analyzed in this report. It must be mentioned that these values are estimates and not directly measured values, so they have to be used with some uncertainty.

Table 14: Heat generation expenditure factor of heat generators in the original building state (NS3031, 2011)

	Before 1956	1956-1970	1971-1980
Heat generation expenditure factor of heat generator			
Direct electricity, DHW ($e_{g,w,1}$)	1.02	1.02	1.02
Direct electricity, space heating ($e_{g,h,1}$)	1.0	1.0	1.0
Wood, space heating ($e_{g,h,3}$)	1.563[6]	1.563[6]	1.563[6]

Table 15: Heat generation expenditure factor of heat pumps (NS3031, 2011)

Heat generation expenditure factor of heat generator	2006 →
Air-to-air heat pump, space heating ($e_{g,h,renovation}$)	0.463
Air-to-water heat pump, DHW ($e_{g,\square,renovation}$)	0.48

The internal heat loads from persons, lighting, domestic hot water and other electrical equipment from dwellings (ϕ_{int}) are based on values given in NS3031 and are set equal to 5.25 W/m^2 (NS3031, 2011).

Heat loss due to heat storage and distribution needs to be included when the required amount of produced heat from a heat generator is calculated. Also the space heating contribution of the ventilation heat as well as the recoverable heat loss from the DHW system should be included. The heat losses lead to an increased level of heat production, while the recoverable heat losses lead to a decreased level of required production. It is beneficial to have as much heat recovery as possible hence giving a lower production of heat from the generator. However, it is limited how low this production can get without changing the building's energy need for space heating. Figure 11 shows the basic principle of the space heating system and the connected heat losses. It must be mentioned that the heating system in the

6 Numbers from (Pettersen , Lars, Wigenstad, & Dokka, 2005)

figure actually is inside the dwelling, so this figure is just made as an illustration of the basic principle.

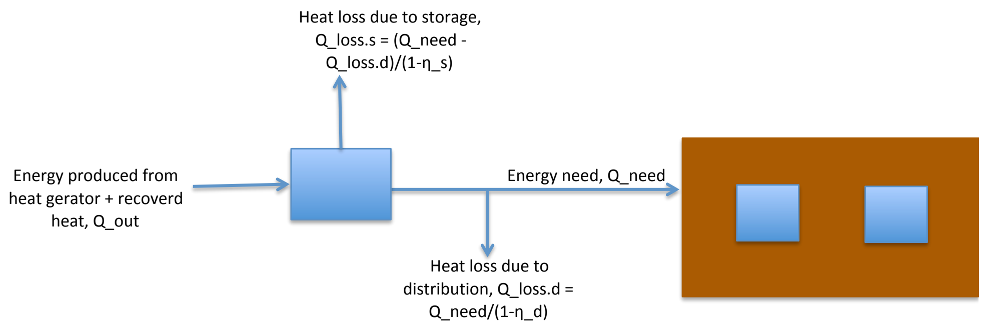


Figure 11: Heating system principles

Standard values from TABULA for annual heat losses from heat storage and distribution are given for both space heating and domestic hot water system. For a typical original apartment block built before 1956 electric heaters are used for space heating as mentioned earlier, and the distribution system is therefore assumed to be decentral. The domestic hot water system (DHW) uses an electrical heater to heat the water and uses a hot water storage tank to store the heat. This technology is the most common one for all time periods evaluated in this report, and the distribution and storage systems are therefore the same for all building typologies. Table 16 shows common values for these energy flows. Since Denmark and Sweden did not have good values for decentral electric hot water systems, German values are used. In Denmark and Sweden district heating is much more common and developed than in Norway, and it was more common to build buildings with centralized heating system due to higher electricity prices.

Table 16: Heat losses due to heating system (TABULA, 2013)

	Before 1956 (kWh/m²a)	1956-1970 (kWh/m²a)	1971-1980 (kWh/m²a)
Heat loss of the space heating storage ($q_{s,h}$)	0	0	0
Heat loss of the space heating distribution ($q_{d,h}$)	0	0	0
Heat loss of the DHW heat storage ($q_{s,w}$)	3.6	3.6	3.6
Contribution of the DHW heat storage loss to space heating ($q_{s,w,h}$)	2.4	2.4	2.4
Heat loss of the DHW distribution ($q_{d,w}$)	4.6	4.6	4.6
Contribution of the DHW heat distribution loss to space heating ($q_{d,w,h}$)	3.0	3.0	3.0

For historical, TEK10- and passive house refurbishments German values for buildings built after 1995 are used. Heat losses due to DHW distribution are therefore set to be 1.4 kWh/m^{2}a, while the contribution of this heat loss to space heating is set to be 0.8 kWh/m^{2}a. For heat losses from the DHW storage tank the value for historical refurbishment is set to be 2.9 kWh/m^{2}a. The contribution of this heat loss to space heating is set to be 1.9 kWh/m^{2}a.

Need for domestic hot water $q_{nd,w}$ is assumed to be the same for all building typologies and is set to be 30 kWh/m^2 per year as given in NS 3031: 2007+A1:2011.

3.2 Methods, variables and input values for LCC calculations

Life Cycle Costing (LCC) compares project cost estimates over several years. In this report the period analyzed is from 2014 to 2050, which corresponds to a period of 36 years. During this period costs due to the initial investment, the use phase and end-of-lifetime activities are included, as illustrated in Figure 12 (Forte, 2012).

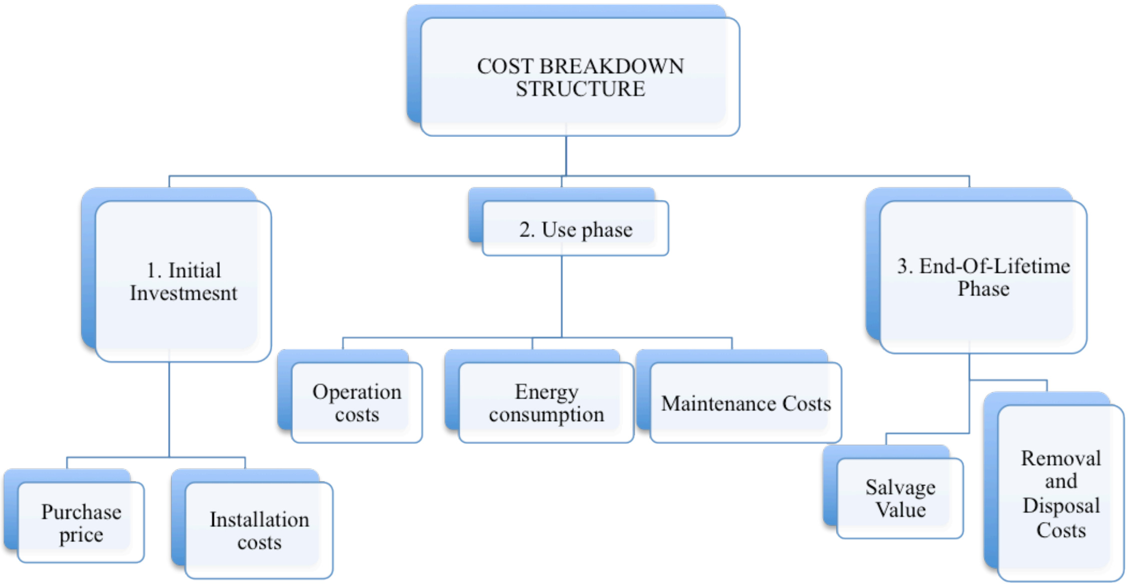


Figure 12: Elements included in a LCC analysis (Forte, 2012)

By performing an LCC analysis on different renovation measures it is possible to find out which measure that is the most profitable one in a long-term perspective. In this study it is focused on the financial evaluation of Energy Efficiency Projects, so costs connected to measures that are not energy related are excluded from the analysis. This is done to simplify the analysis and focus on the parts that are of most interest for this thesis (Forte, 2012).

When performing an LCC analysis it is beneficial to follow six different steps (Forte, 2012):

1. Define the scope of the analysis
2. Identify relevant cost components
3. Gather data and derive cost estimates
4. Calculate key financial indicators (Net present value (NPV))
5. Perform a risk and uncertainty analysis
6. Take the best decision

After finishing step 4, in this case to calculate the net present value of different renovation projects, it is necessary to perform a risk and uncertainty analysis as some of the parameters and cost information are given with a quite large uncertainty. The end result may therefore be completely different if a cost value is increased or decreased (Forte, 2012).

The renovation package with the lowest life-cycle cost is considered the best solution economically. The most challenging task in an LCC analysis is to determine the economic effects of alternative designs of buildings and building system and to quantify these effects and express them in money amounts (Fuller, 2010). Typical costs that should be included in an LCC are the initial costs that include all costs connected to investing in a certain renovation measure, the operation and maintenance costs, the replacement costs of a certain measure if the components have shorter lifetime than the analysis period, and residual values (the value of the investment in the final year of the analysis period) (Fuller, 2010).

Initial costs

Initial cost is in this report defined as the extra investment costs connected to a certain renovation measure for a building. This cost is always implemented in the first year of the analysis period. Only costs that can be directly connected to improved energy efficiency are included in the investment cost. More information about investment costs connected to different renovation measures can be found in chapter 3.2.2.

Energy costs

Energy costs are connected to the use phase of the building and in this study the energy costs included are costs due to space heating and domestic hot water. Costs connected to lighting and cooling is not included, as renovation projects for these parts of the building are not analyzed.

The energy costs are dependent on the energy source, the energy price and the energy consumption of the building. Low energy consumption generally gives a low total energy cost. However, the total energy costs are also dependent on the energy price, and since this is a very uncertain parameter over time a sensitivity analysis on this parameter is completed (see chapter 4.2.2.2). In this project there are three different energy sources used; electricity, wood and district heating. The electricity price is set to be 0.893 NOK/kWh (SSB, 2014), the price of wood for a wood stove is set to be 0.625 NOK/kWh (Hofstad, 2007) and the price of district heating is set to be 90 % of the electricity price due to § 5-5 in the Norwegian Energy Act that says that the price of district heating should not be higher than the price of the electrical heating in the relevant supply area (Econ, 2010).

Operation and maintenance costs

Operation costs connected to different energy related refurbishment measures include costs connected to operation of these measures. For the building envelope it is assumed that there are no operation costs, but if a balanced ventilation system is installed there may be some costs connected to operation. More information about this is given in chapter 3.2.2.

Replacement costs

Since an LCC analysis is performed over a defined period of time some energy related refurbishment measures reaches their end of lifetime before the analysis period is completed. For these measures it is necessary to re-install the measure. Since the analysis period is 36 years in this thesis almost all refurbishment measures have to be re-installed at least one time during the analysis period.

Residual values

The residual value of a system/component is the remaining value at the end of the analysis period. Residual values can be based on value in place, resale value, salvage value or disposal costs. The residual value of a system with remaining useful life in place can usually be calculated by linearly prorating its initial costs. For example, for a system with an expected useful lifetime of 15 years, which was installed 5 years before the end of the study period, the residual value would be approximately 2/3 of its initial cost (Fuller, 2010).

Net present value (NPV)

A life cycle costing analysis is made to facilitate a decision: which alternative is the best choice in a long-term perspective? To be able to make a proper decision it is important to compare the net present value of each project, and the principle of NPV is examined thoroughly in this chapter. The net present value is the total cost over the entire period and is calculated as the sum of the present value of each year's cost. The reason why it is necessary to use present value and not just sum up the yearly cost is because of the time value of money. It is always beneficial to get 200 NOK today instead of in five years. The reason for this is that it is possible to put the money in a bank and get profit on them (Forte, 2012).

Each cost that occurs in the future have a Present Value (PV) that is different from its Future Value (FV). The relation between the PV (in year 0) and the FV (in year k) is given in Equation 3.

Equation 3: Calculation of present value (PV)

$$PV = \frac{FV}{(1+i)^k}$$

where i is the discount rate.

The most important parameter to determine the Present Value is the discount rate, i. The present value of a future value is very dependent on this parameter since the present value gets low if the discount rate is high and high if the discount rate is low. The discount rate used in this project is 5 % (Førland-Larsen, 2012). To be able to compare cash flows that are incurred at different times during the life cycle of a project, they have to be made time-equivalent. The discount rate represents the investor's minimum acceptable rate of return (Fuller, 2010).

The most important financial indicator in an LCC analysis is the net present value. It is defined as the sum of the present values (PVs) of the individual cost components, whereby each instance of each cost component is discounted according to year 0. The NPV can be calculated using the following equation, where C_0 is the initial investment (in year 0) and C_K is the sum of all relevant cost components that occurs in year k.

Equation 4: Calculation of net present value

$$NPV = C_0 + \sum_{k=1}^{T} \frac{C_k}{(1+i)^k}$$

T corresponds to the time horizon of the life cycle costing analysis and i represents the discount rate. The input values for the net present value calculation are investment costs for the analyzed renovation measure, the operation and maintenance costs, and the energy costs.

3.2.1 Component composition of the apartment blocks analyzed

The buildings analyzed in the LCC model are three typical apartment blocks built before 1980 and have the properties given in Table 12. Since 84 %, 75 % and 67 % of the apartment blocks built before 1956, between 1956-1970 and 1971-1980 respectively are partly refurbished (see chapter 2.4) the analysis includes refurbishments on six different kinds of buildings. To be able to figure out the investment cost of different renovation measures it is necessary to analyze the component composition of the building types analyzed before renovation. All building types, both in original and historical refurbished state, are assumed to use a natural ventilation system, as mentioned in chapter 3.1.1. All buildings are also constructed with panel heaters and therefore only a decentral heating system.

Apartment blocks built before 1956

In Norway there are about 20 194 apartment blocks built before 1956 that have the properties given in Table 12. Of these buildings 16 % are in original state and 84 % are in historical refurbished state (see chapter 2.4).

Original state

Typical for these buildings in original state are that they have (Prognosesenteret AS & Entelligens AS, 2012):

- Exterior walls that either are uninsulated brick or concrete with 75 mm wood wool board
- Roof and floor that consists of 150x120 mm beams with stub clay. Both roof and floor are not directly connected to the external environment. They are connected to an unheated basement or attic. This is however taken into consideration when the effective U-values are calculated
- Windows made of 4 mm glass, 16 mm cavity and then 4 mm of glass again (two tier Insulating Glass). This type of window typical has a U-value of 2.6 W/m^2K (Thyholt, 2002).

Historical refurbished state

A historical upgrade includes (Prognosesenteret AS & Entelligens AS, 2012):

- 50 mm extra mineral wool insulation in external walls
- Replacing the stub clay in roof and floors with 100 mm mineral wool
- Replacing existing windows with better isolated windows (U-value ~ 2.0 W/m^2K)

Except for these changes this building type has the same component composition as the building in original state.

Apartment blocks built during the period 1956-1970

6 645 of the apartment blocks that exist today are from this period, where 25 % are in original state.

Original state

Buildings in original state from this period typical have the following component composition (Prognosesenteret AS & Entelligens AS, 2012):

- Exterior walls in concrete with 100 mm aerated concrete,
- Roof that are made in concrete with 100 mm mineral wool.

- Floors that are made in concrete and insulated with 50 mm mineral wool.
- Windows that are made of 4 mm glass, 16 mm cavity and then 4 mm of glass again (two tier Insulating Glass). This type of window typical has a U-value of 2.6 W/m^2K (Thyholt, 2002). 2.6 W/m^2K is a normal U-value for windows installed during the 60s (Enova b, 2012).

Historical refurbished state

A historical upgrade includes (Prognosesenteret AS & Entelligens AS, 2012):

- 100 mm extra mineral wool insulation in the external walls
- 50 mm extra mineral wool on the upper side of the external roof and floor.
- Replace existing windows with better insulated windows (U-value ~ 2 W/m^2K)

Except for these changes this building type has the same component composition as the building in original state.

Apartment blocks built during the period 1971-1980

There are 3 768 apartment blocks today that are from this time period, where 33 % of these are in original state.

Original state

Typical for these buildings in original state are that they have (Prognosesenteret AS & Entelligens AS, 2012):

- Exterior walls that consist of timber frame in wood, 100 mm mineral wool and 50 mm thermal bridge breaker
- Roof made in concrete with 180 mm mineral wool
- Floor made in concrete and insulated with 100 mm mineral wool. The floor is not directly connected to the external environment. It is connected to an unheated cellar. This is however taken into consideration when the effective U-value is calculated,
- Windows are assumed to be the same as for the previous building typologies.

Historical refurbished state

A historical upgrade includes (Prognosesenteret AS & Entelligens AS, 2012):

- 100 mm extra mineral wool insulation (satisfy TEK10)
- Replacing 180 mm mineral wool with 250 mm mineral wool in roof (satisfy TEK10)
- 50 mm extra mineral wool in floor
- Replacing existing windows with better isolated windows (U-value ~ 1.6 W/m^2K)

The average U-value for windows after historical upgrade is assumed to be the same as for windows installed during the time period 2001-2010, and is therefore set equal to 1.6 W/m^2K (Prognosesenteret AS & Entelligens AS, 2012).

3.2.2 Description of different renovation packages

Fourteen different renovation packages have undergone an LCC to be able to make a qualified and good decision for the best refurbishment measures. This chapter gives a detailed description of what is included in the renovation packages. Some of the renovation packages are combinations of others. Since it is assumed that the building envelope is changed whether the quality is improved or not costs connected to demolition and re-construction of the building envelope is not included in the analysis. Only costs connected to measures that give increased energy efficiency are included in the analysis. This means that only the extra cost connected to increasing the insulation thickness in walls etc. is included in the LCC analysis. However, it should be mentioned that this assumption makes it cheaper to improve the building envelope, since costs connected to demolition and re-construction is removed from the equation. Demolition and re-construction of concrete walls typical costs 238.4 NOK/m^2 and 845 NOK/m^2 respectively (Jensen & Rudén, 2013).

The different renovation packages analyzed in this report are given in Table 17.

Table 17: Overview of the renovation packages analyzed in this report

Renovation package	Description
0	No energy-related upgrades except improving the U-values of the windows to 1.4 W/m^2K
1	Upgrading windows to passive house level
2	TEK10 envelope upgrade
3	Passive house envelope upgrade
4	Installation of air-to-air heat pump
5	Installation of balanced ventilation system with 70 % heat recovery
6	TEK10 envelope upgrade + installation of air-to-air heat pump
7	TEK10 envelope upgrade + installation of balanced ventilation system with 70 % heat recovery
8	TEK10 envelope upgrade + Installation of water-based heating system with radiators + connecting to district heating
9	Passive house envelope upgrade + installation of air-to-air heat pump
10	Passive house envelope upgrade +installation of balanced ventilation system with 80 % heat recovery
11	Passive house envelope upgrade + Installation of water-based heating system with radiators + connecting to district heating
12	Passive house envelope upgrade + Installation of water-based heating system + installation of solar collectors
13	Passive house envelope upgrade +Installation of water-based heating system with radiators + installation of air-to-water heat pumps
14	Passive house envelope upgrade + Installation of water-based heating system + installation of solar collectors + installation of balanced ventilation system with heat recovery

Renovation package 0 doesn't include any measures that decrease the yearly energy use except for required reduction in the U-value of the windows due to the fact that it is difficult and unrealistic to get windows with a higher U-value than 1.4 W/m^2K (Tindevindu, 2014). However, it is assumed that old building components like exterior walls, roof etc. are replaced with new materials but without any upgrades of the building envelope. Costs connected to replacement of water heaters are included in each case since these costs are different depending on the heating system. In existing buildings where a water-based heating system is not installed the water heater is heated up directly by electricity (Braathen, 2013). The costs included in renovation package 0 are therefore re-installation cost of electric panel heaters for space heating and storage tank/heater for domestic hot water, as well as costs connected to installation of new windows. These costs are given in Table 18.

Table 18: Cost information of panel heaters for space heating, storage tank/heater for domestic hot water and windows with U-value of 1.4 W/m^{2}K

	Investment cost
Panel heaters (NOK/m^2 BRA)	157.5[7]
Water heaters/storage tank for domestic hot water (NOK/unit)	6 400[8]
Windows with U-value = 1.4 W/m^{2}K (NOK/m^2 window)	3 195

Three different window types are used in the different renovation packages, one with a U-value of 1.4 W/m^{2}K (given in Table 18), one with a U-value of 1.2 W/m^{2}K (satisfy TEK10), and one with a U-value of 0.8 W/m^{2}K (satisfy the passive house standard). The costs of the TEK10- and passive house approved windows are given in Table 19.

Table 19: Cost information for TEK10- and passive house approved windows

Windows type	Cost (NOK/m^2 window area)
TEK10-windows (1.2 W/m^{2}K)	3 305[9]
Passive house windows (0.8 W/m^{2}K)	6 347 [10]

As shown in the table, investing in a window that qualifies the passive house standard is twice as expensive as investing in a window that qualifies TEK10. However, it must be mentioned that there may be cheaper windows that satisfy the passive house standard, and this can have an impact on the results from the LCC calculations. Costs connected to doors are assumed to be similar to the costs connected to windows, and are therefore for simplicity set equal to the window price. However, the lifetime is somewhat different. Windows are assumed to have an average lifetime of 29 years, while doors are assumed to have an average lifetime of 20 years (Holte AS, 2014).

[7] Source: (Holte AS, 2014) + 25 % mva
[8] Source: (Braathen, 2013)
[9] Source: (Tindevindu, 2014)
[10]Source: (Jensen & Rudén, 2013)

3.2.2.1 TEK10-upgrade of the building envelope

Upgrading the building envelope to TEK10-level includes different measures depending on the envelope quality in pre-refurbished state. If the building envelope generally has high U-values more insulation is required than if the building envelope has low U-values.

Table 20 shows the different measures that are necessary to upgrade the buildings to TEK10-level. Chapter 2.2 shows what is required to achieve a TEK10 standard. More information about the U-values of the envelope in pre-refurbished state can be found in Table 12 (see page 35). This sort of renovation is included in renovation package 2, 6, 7 and 8 (see Table 17 at page 45).

Table 20: Measures necessary to achieve a TEK10 fulfilled building envelope (Prognosesenteret AS & Entelligens AS, 2012)

	Built before 1956		**Built between 1956 and 1970**		**Built between 1971 and 1980**	
	Original state	**Historical refurbished state**	**Original state**	**Historical refurbished state**	**Original state**	**Historical refurbished state**
External walls	200 mm extra mineral wool	150 mm extra mineral wool	200 mm extra mineral wool	100 mm extra mineral wool	100 mm extra mineral wool	No measures necessary
Floor	Replacing stub clay with 200 mm mineral wool[11]	Replacing stub clay with 100 mm mineral wool	150 mm extra mineral wool[11]	100 mm extra mineral wool[11]	100 mm extra mineral wool[11]	50 mm extra mineral wool[11]
Roof	Replacing stub clay with 100 mm mineral wool and adding 150 mm mineral wool at cold attic	150 mm mineral wool at cold attic	150 mm extra mineral wool[11]	100 mm extra mineral wool[11]	Replacing 180 mm mineral wool with 250 mm mineral wool	No measures necessary
Windows and doors	Change to windows and doors with U-value of 1.2 W/m²K	Change to windows and doors with U-value of 1.2 W/m²K	Change to windows and doors with U-value of 1.2 W/m²K	Change to windows and doors with U-value of 1.2 W/m²K	Change to windows and doors with U-value of 1.2 W/m²K	Change to windows and doors with U-value of 1.2 W/m²K

The insulation thickness is calculated up to closest upper 50, which means that if the required extra insulation thickness is calculated to be 170 mm the insulation thickness is set to be 200 mm. This is done to ensure that the TEK10 requirement is fulfilled (see Appendix A).

TEK10 requires a thermal bridge value lower or equal to 0.06 W/m^2K. It is therefore anticipated that the thermal bridge value decreases down to TEK10-level after a TEK10-refurbishment (Kommunal- og regionaldepartementet, 2010). Since TEK10 require a leakage rate lower than 1.5 air exchanges per hour, it is assumed that the TEK10-refurbishments will lead to a reduction in additional air exchange rate so that this requirement is fulfilled. A

[11] See appendix A

leakage rate (n_50) of 1.5 1/h gives an additional air exchange rate of 0.1 1/h, which indicate a reduction of 0.3 1/h (Loga & Diefenbach, 2012).

Cost information

Table 21 shows the extra costs that is necessary for each building type to achieve a TEK10 standard on the building envelope. This cost parameter includes costs due to extra insulation material, transportation and labor. The cost given in this table includes material cost, transport cost and labor costs. More detailed information on each cost type can be found in appendix C.

Table 21: Extra costs (compared to renovation package 0) connected to TEK10 envelope upgrade (See appendix C)

	Built before 1956		**Built between 1956 and 1970**		**Built between 1971 and 1980**	
	Original state	**Historical refurbished state**	**Original state**	**Historical refurbished state**	**Original state**	**Historical refurbished state**
External walls (NOK/m^2 BRA)	258	215	225	152	58.3	0
Floor (NOK/m^2 BRA)	36	22.8	27.6	22.9	22.9	18.2
Roof (NOK/m^2 BRA)	40.1	27.6	28	22.9	20.1	0
Windows (NOK/m^2 BRA)	22.1	22.1	16.6	16.6	16.5	16.5
Doors (NOK/m^2 BRA)	0.8	0.8	0.8	0.8	0.7	0.7
Total envelope upgrade cost (NOK/m^2 BRA)	357	288.3	298	215.2	118.5	35.4

3.2.2.2 *Passive house upgrade of the building envelope*

As for the TEK10-envelope upgrade there are different measures necessary to achieve a passive house standard depending on the quality of the building envelope in original state. The measures necessary to achieve a building envelope that satisfies the passive house standard for the building types analyzed in this project are given in Table 22. This sort of renovation is included in renovation package 3, 9, 10, 11, 12, 13 and 14 (see Table 17), where all packages except for renovation package 3 includes extra measures like installation of heat pumps or balanced ventilation system.

Table 22: Measures necessary to achieve a passive house standard (see Appendix A for calculations)

	Built before 1956		**Built between 1956 and 1970**		**Built between 1971 and 1980**	
	Original state	**Historical refurbished state**	**Original state**	**Historical refurbished state**	**Original state**	**Historical refurbished state**
External walls	300 mm extra mineral wool	250 mm extra mineral wool	300 mm extra mineral wool	200 mm extra mineral wool	150 mm extra mineral wool	100 mm extra mineral wool
Floor	Replacing stub clay with 400 mm mineral wool	Replacing stub clay with 300 mm mineral wool	350 mm extra mineral wool	300 mm extra mineral wool	300 mm extra mineral wool	250 mm extra mineral wool
Roof	Replacing stub clay with 400 mm mineral wool	300 mm mineral wool at cold attic	300 mm extra mineral wool	250 mm extra mineral wool	Replacing 180 mm mineral wool with 400 mm mineral wool	150 mm extra mineral wool
Windows and doors	Change to windows and doors with U-value 0.8 W/m^2K	Change to windows and doors with U-value 0.8 W/m^2K	Change to windows and doors with U-value 0.8 W/m^2K	Change to windows and doors with U-value 0.8 W/m^2K	Change to windows and doors with U-value 0.8 W/m^2K	Change to windows and doors with U-value 0.8 W/m^2K

In the energy calculations it is anticipated that these measures lead to a decrease in thermal bridge value, so that the passive house requirement of a value below 0.03 W/m^2K is achieved (NS3700, 2013). The passive house standard require a leakage rate lower than 0.6 1/h, which gives an additional air exchange rate of 0.05 1/h (Loga & Diefenbach, 2012). It is assumed that the buildings achieve this kind of tightness after the refurbishments.

Cost information

Table 23 shows the extra costs that is necessary for each building type to achieve a passive house standard on the building envelope. The costs given in this table includes material cost, transport cost and labor costs. More detailed information on each cost type can be found in appendix C.

Table 23: Extra costs (compared to renovation package 0) connected to passive house envelope upgrade (See appendix C)

	Built before 1956		Built between 1956 and 1970		Built between 1971 and 1980	
	Original state	**Historical refurbished state**	**Original state**	**Historical refurbished state**	**Original state**	**Historical refurbished state**
External walls (NOK/m^2 BRA)	364.2	320.3	317.8	239.7	122.5	97.5
Floor (NOK/m^2 BRA)	56.8	47	52.2	47	47	40.4
Roof (NOK/m^2 BRA)	56.8	47	47	40.4	35.5	27.6
Windows (NOK/m^2 BRA)	377.9	377	283.5	283.5	282.4	282.4
Doors (NOK/m^2 BRA)	13.3	13.3	14.3	14.3	12.6	12.6
Total envelope upgrade cost (NOK/m^2 BRA)	869	804.6	714.8	624.9	500	460.5

Compared to costs connected to upgrading the windows to passive house level given in the Asplan Viak report, the extra cost used in this project is up to 3 times as high (Førland-Larsen, 2012), which implies that the cost used for passive house windows in this report may be a bit too high. Lowering this cost parameter may therefore increase the profitability of the renovation packages that include installation of this window type.

3.2.3 Costs connected to renovations done on the heating and ventilation system

Many of the renovation packages analyzed in this report include changes in the heating system. These changes include installation of heat pumps, solar collectors, customer centrals for district heating or balanced ventilation systems. For several of these measures it is necessary to install a water-based heating system in the building. Costs connected to installation of heat pumps etc. are dependent on the dimensioning size, which again is dependent on the building's energy need for space heating and domestic hot water. The necessary size of the equipment is therefore given in chapter 4.1.2, but the calculation method is described in this chapter.

3.2.3.1 Installation of water-based heating system

Installation of a water-based heating system is necessary for many of the renovation packages analyzed in this report since many of the heating sources can only transfer heat through water. This is the case for air-to-water heat pumps, customer centrals for district heating and solar collectors. Changing to a water-based heating system can be a bit challenging in existing buildings since a pipeline network through the building has to be installed (see chapter 2.7.6). However, installing a water-based heating system is required for all new buildings with a useful heated floor area over 500 m^2 (Kommunal- og regionaldepartementet, 2010). Installing a water-based heating system is expensive, but gives more flexibility to the building when it comes to energy supply. For apartment blocks it is estimated that installing a complete water-based heating system with radiators costs approximately 810.5 NOK per m^2 heated floor area when 25 % VAT is included (Jensen & Rudén, 2013), and typical have a lifetime of 35 years (Holte AS, 2014).

3.2.3.2 Installation of air-to-air heat pumps

Installation of heat pumps alone don't lead to a lower heating demand for the building, it only gives a reduction in delivered energy since approximately two-thirds of the heat produced from a heat pump comes from low energy heating sources like external air. However, the efficiency of the heat pump decreases when the outdoor temperature decreases, as mentioned in chapter 2.7.4. This means that it is always necessary to use another heating source to cover the peak loads. Implementation of heat pumps generally reduces the building's net energy need for space heating. Then again, how well a heat pump function is dependent on operation, and people tend to increase the level of comfort when using a heat pump. As a consequence of this the savings tends to be smaller than optimal possible (Prognosesenteret AS & Entelligens AS, 2012). For the calculations it is set that the heat pump can cover 90 % of the energy need for space heating, while the last 10 % is covered by direct electricity.

Sizing and cost information

The heat pumps should be dimensioned to cover 60 % of the maximum heating demand, which typical corresponds to 80-90 % of the building's energy use (NTNU and SINTEF, 2007). The peak load is covered by direct electricity through panel heaters, and the cost of installing these can be found in Table 18 at page 46. The size of the heat pump can be calculated by using Equation 5.

Equation 5: Calculation of dimensioning heat pump power for air-to-air heat pumps

$$P_{dim} = 0.6 \cdot (H_{ve} + H_{tr}) \cdot (T_{in} - DOT) \qquad [W]$$

where

H_{ve} is the overall heat transfer coefficient by ventilation [W/K] (see Equation 1)

H_{tr} is the overall heat transfer coefficient by transmission [W/K] (see Equation 2)

T_{in} is the indoor temperature [K]

DOT is the design outdoor temperature [K]

The cost profiles are given for heat pumps with a capacity of 3 kW and 4 kW (Jensen & Rudén, 2013). It is anticipated that the price per heat pump decreases when the desired capacity decreases. It is assumed that the prize of one heat pump with a capacity of 3 kW is the same as the price of two heat pumps with a capacity of 1.5 kW. This assumption may though be a bit misleading and the costs connected to smaller heat pumps may be higher than anticipated in this analysis. The necessary capacity and number of heat pumps for each of the building types after renovation package 4, 6 and 9 is given in Table 29 and Table 30 respectively (see page 63).

The heat pump price includes costs connected to the heat pump itself and to installation of the equipment. An air-to-air heat pump with a capacity of 3 kW typically have a cost of 25 402 NOK/unit when 25 % VAT is included, while an air-to-air heat pump with a capacity of 4 kW typically have a cost of 32 921 NOK/unit (Jensen & Rudén, 2013). The lifetime of these heat pumps are set to 10 years (NOVAP a , 2012), and the yearly maintenance costs are set to be 2.5 % of the investment cost (Statsbygg, 2013).

3.2.3.3 Installation of air-to-water heat pumps

The benefit of using an air-to-water heat pump instead of an air-to-air heat pump is that it is possible to cover the domestic hot water as well as the space heating demand. However, if this heat pump alone should cover parts of the space heating demand it is necessary to install a water-based heating system in the building. Installation of a water-based heating system in an apartment block is anticipated to be 810 NOK/m^2 heated floor area (Jensen & Rudén, 2013). Since the heat pump is only dimensioned to cover 90 % of the heating demand, an electric boiler is installed to cover the peak loads.

Sizing and cost information of the heat pump

An air-to-water heat pump is dimensioned in the same manner as an air-to-air heat pump except that domestic hot water is included in the dimensioning (see Equation 6).

Equation 6: Calculation of dimensioning heat pump power for air-to-water heat pumps

$$P_{dim} = 0.6 \cdot ((H_{ve} + H_{tr}) \cdot (T_{in} - DOT) + P_w \cdot BRA) \qquad [W]$$

where

H_{ve} is the overall heat transfer coefficient by ventilation [W/K] (see Equation 1)

H_{tr} is the overall heat transfer coefficient by transmission [W/K] (see Equation 2)

T_{in} is the indoor temperature [K]

DOT is the design outdoor temperature [K]

P_w is the heating effect for domestic hot water (W/m^2)

BRA is the heated floor area (m^2)

An air-to-water heat pump with a capacity of 6 kW have an investment cost of 89 000 NOK (TOSHIBA, 2014). The necessary amount of heat pumps of this size is given in chapter 4.1.2.1. An air-to-water heat pump typical has a lifetime of 15 years (NOVAP b, 2012) and the yearly maintenance costs are set to be 2.5 % of the investment cost (Statsbygg, 2013).

3.2.3.4 Connecting to the district heating grid

Connecting a building to the district heating grid requires installation of a heat exchanger in the building that transfer heat from the district heating grid to the water system in the building. It is possible to use the water from the district heating grid directly, but due to safety reasons it is more common to use two hydraulic separated water systems (see chapter 2.7.7). The installation cost of installing a heat exchanger and connecting this to the district heating grid varies on the required size of the heat exchanger (Rosenberg, 2010). Since the price of district heating is lower and the emission rate can be lower (if the majority of the heating sources are renewable) it can be beneficial to change from direct electricity to district heating. It is also beneficial to offload the electricity grid to increase the security of supply.

Sizing and cost information of heat exchanger for district heating

The heat exchanger for district heating should have enough heating effect to cover the need for space heating and domestic hot water. The following equation is used to calculate the heating effect for the heat exchanger:

Equation 7: Dimensioning power requirement for a heat exchanger

$$P_{dim} = (H_{ve} + H_{tr}) \cdot (T_{in} - DOT) + P_{hot\,water} \cdot BRA \quad \text{[W]}$$

where

H_{ve}	is the overall heat transfer coefficient by ventilation [W/K] (see Equation 1)
H_{tr}	is the overall heat transfer coefficient by transmission [W/K] (see Equation 2)
T_{in}	is the indoor temperature [K]
DOT	is the design outdoor temperature [K]
$P_{hot\,water}$	is the heating effect for domestic hot water and is set equal to 5.1 W/m^2 heated useful floor area (NS3031, 2011)
BRA	is the heated useful floor area in the building [m^2]

The necessary size of the heat exchanger for the different apartment blocks after renovation package 8 and 11 is given in Table 35 in chapter 4.1.2.3.

The cost of connecting a building to the district heating grid is, as mentioned before, depending on the size of the heat exchanger. However, for heat exchangers with a capacity below 50 kW it is assumed that the prize stays constant. The lifetime of the heat exchanger is set to be 18 years (Holte AS, 2014). Table 24 shows an overview of the installation costs estimated for different district heating customers with different heating need (Rosenberg, 2010).

Table 24: Installation cost (district heating) for different heating effects (Rosenberg, 2010)

Heating effect (kW)	Total cost, district heating connecting
50	115 500
100	131 250
150	141 750
200	157 500

Yearly maintenance costs due to the heat exchanger is estimated to be 2 % of the investment costs (Lunden, 2013). When distributing heat through a water-based heating system a different water heater for domestic hot water is used, and the installation cost of this kind of heater/storage tank is 11 250 NOK/unit (Braathen, 2013). It is anticipated that one water heater is installed in each apartment.

3.2.3.5 Installation of solar collectors

Installation of solar collectors is included in renovation package 12 and 14, and requires installation of a water-based heating system (see chapter 3.2.3.1) and installation of an electric boiler to cover the peak load.

Sizing and cost information for solar collector and electric boiler

As mentioned in chapter 2.7.1 it is not possible for the solar collector to cover the entire heating demand since the production is low during winter when the heating demand is highest. But it is anticipated that the solar collector can cover approximately 60 % of the total heating demand during the year (Andersen I., 2008). An electric boiler is installed to cover the remaining heating demand. It is anticipated that a small solar collector is able to produce 3274 kWh per year and a big solar collector is able to produce 6548 kWh per year (Jensen & Rudén, 2013). Several solar collectors of these sizes are installed so that the total production from the solar collectors corresponds to 60 % of the total heating demand. A solar collector system with a production capacity of 3274 kWh per year have an investment cost of about 88 974 NOK, while a solar collector system with a production capacity of 6548 kWh/year have an investment cost of about 164 729.8 NOK (including 25 % VAT) (Jensen & Rudén, 2013). Table 32 and Table 33 in chapter 4.1.2.2 (see page 64) shows the required production from the solar collectors for each apartment block for renovation package 12 and 14 as well as the calculated total cost of the installation (NOK/m^2 BRA).

A solar collector typical has a lifetime of 30 years (Øvereng, 2003). The yearly maintenance cost of the solar collector system is set to be 0.5 % of the investment cost (Berner, 2013). The electric boiler should be dimensioned to cover the peak load, and the necessary size of the electric boiler is given in Table 36 (see page 65) and calculated by using Equation 7. The installation cost for an electric boiler is set to be 925 NOK/kW and the yearly maintenance costs are set to be 107 NOK/kW (Hofstad, 2007). An electric boiler also has an average lifetime of 30 years (THEMA, 2012).

When it comes to storage tank/heater for domestic hot water a new tank special made for systems that includes solar collectors is used, and this storage tank/heater has an investment cost of 13 750 NOK (Braathen, 2013).

3.2.3.6 Installation of a balanced ventilation system

Installing a balanced ventilation system in an already existing apartment block can be very complicated since it requires an advanced pipeline system. The cost of installing a balanced ventilation system in an apartment block is assumed to be 790 NOK/m^2 BRA (included 25 % VAT) (Jensen & Rudén, 2013). A balanced ventilation system typical has a lifetime of 23 years (see appendix E)

In this Master thesis it is assumed that the balanced ventilation system is equipped with a heat exchanger with 70% efficiency, so that 70 % of the heat from the exhaust air is transferred to the cold inlet air. TEK10 require a minimum ventilation air rate of 1.2 m^3/hm^2 when the building is in use and an air rate of 0.7 m^3/hm^2 when the building is not in use (Kommunal- og regionaldepartementet, 2010). For the energy calculations an air change rate of 0.4 1/h is used. This is based on the assumptions that the building is in use 20 hours during the day and not in use 4 hours of the day. The ventilation air rate might though be higher in a balanced ventilation system, but due to lack of detailed information of actual air change rates in balanced ventilation systems a value of 0.4 1/h is kept in all of the calculations.

3.3 Energy scenario model for the development of energy use in apartments built before 1980

To be able to calculate the dynamic development of energy use in the building stock analyzed in this report data from the segmented building stock model made by Nina Sandberg has to be used as well as energy data from the energy calculation model made by the author (see appendix D1).

3.3.1 The segmented building stock model

The purpose of this model is to give a prognosis of the future development of residential buildings in Norway. The model gives output on how many apartments that is constructed each year, as well as demolished. It is possible to divide the total period (that is from 1800 to 1900) into five cohorts, which makes it possible to see how many of the buildings built in a certain period that will be refurbished or demolished in the future. However, the model only tells how many apartments that are refurbished each year, and cannot separate buildings that have already been refurbished and buildings that have not. Since the renovation probability function is calculated by using normal distribution it is difficult to make an accumulated building stock model that shows the future development of renovated buildings and not renovated buildings when the analyze period is longer than the renovation cycle. This is because it is then not possible to just summarize the total apartments that are renovated each year, because some of the apartments are then counted twice. Because of this weakness with the model it is decided to only look at a 40 years renovation cycle with a standard deviation of 10 years. The total amount of apartments renovated between 2012 and 2050 is then calculated to be 73 %, 70 % and 77 % for apartment blocks built before 1956, between 1956-1970 and 1971-1980 respectively (see appendix D3). It is important to remember that the model quantifies number of apartments, not number of apartment blocks. This means that the energy use per apartment has to be used, not the total energy use per apartment block. The demolition probability function is assumed to follow a weibull distribution since this kind of distribution is seen most suitable for demolition of dwellings. An average lifetime of 125 years is used in the model (Sandberg, Satori, & Brattebø, 2014).

The required inputs to the segmented building stock model are past and future trends in population and persons per dwellings. Technical indicators like the technical lifetime of the buildings and renovation intervals are also required (Sandberg, Satori, & Brattebø, 2014).

3.3.2 Dynamic energy and emission model for apartment blocks built before 1980

This model, made by the author, uses, as mentioned over, inputs from the segmented building stock model and the energy calculation model. The required inputs from the segmented building stock model is the calculated apartments built in each of the specified periods, amount of these building types demolished up until today and from today to 2050, and the amount renovated each year between 2012 and 2050. The input required from the energy calculation model is energy use for space heating and domestic hot water for all of the specified building types before and after renovation. For apartment blocks built before 1956 it is anticipated that 84 % is in historical refurbished state, while 16 % is in original state. For apartment blocks built between 1956 and 1970, and 1971 and 1980 it is anticipated that 75 % and 67 % respectively are in historical refurbished state (Prognosesenteret AS & Entelligens AS, 2012). Since it is the energy and emission development for the total stock of the specified building type that is analyzed it is important to use average values for energy sources. The energy source composition for each of the building types analyzed is given in Table 25.

Table 25: Average energy composition for apartment blocks built before 1956 (Prognosesenteret AS & Entelligens AS, 2012)

	Before 1956	1956-1970	1971-1980
Direct electricity	78%	80%	85%
Wood	8%	5%	4%
Oil	9%	9%	6%
Heat pump	5%	6%	5%

Three different scenarios on how the future energy and emission development can be for the three building types are analyzed. A worst case scenario, where the only energy related renovation done to the buildings are minor window improvements, is included to be able to see the effect of implementing other measures. A best case scenario, where all buildings that undergo a refurbishment are upgraded to passive house level with 70 % heat recovery in the ventilation system as well as installation of a solar collector with an electric boiler to cover the peak loads, is also evaluated to see the optimal energy saving potential. The last future scenario analyzed in this project is a realistic development, where some of the buildings are upgraded to TEK10 standard and some to passive house standard. Some of the buildings are implemented with a heat pump and some with heat recovery in the ventilation system. It is though assumed that all of the buildings that undergo a renovation upgrade their building envelope to either TEK10 or passive house level. Installation of air-to-air heat pumps, solar collectors, heat exchangers for district heating or balanced ventilation systems with 70-80 % heat recovery is added as extra measures for some buildings. The renovation packages chosen in the "realistic" future scenario are based on the results from the NPV and is further discussed in chapter 4.3.3.

3.4 Carbon emission calculations

The emission model is made quite simple, as the LCC took more time than first anticipated. Only emissions connected to the use phase is included in the analysis. This means that emissions connected to production and installation of different renovation measures is not included. This can lead to a better carbon footprint for some measures since some of the measures may have emissions connected to production of the materials used in the measure. This is for instance the case for installation of solar collectors and solar cells. However, studies have shown that during the entire lifetime of a building it is the energy intensity in the use phase that is the main source of negative environmental impact. Polish studies also shows that traditional buildings have 3.6 times higher energy consumption than passive houses (Pajcheowski, Noskowiak, Lewandowska, & Strykowski, 2013). In this project it is calculated that buildings built before 1956 in original state have approximately 3.2 times higher energy consumption than passive houses (see page 66).

The average energy composition for apartment blocks built before 1980 are given in Table 25. Since some of the buildings are assumed to be connected to the district heating grid after renovation the emission factor for district heating is included. The emission factors used for the relevant energy sources used in this project are given in Table 26.

Table 26: Emission factors for different energy sources

	Emission factor (kg CO_2-equivalents/kWh)
Electricity (Norwegian mix)[12]	0.05
Electricity (Nordic mix)[12]	0.2
Electricity (European mix)[12]	0.542
Wood[12]	0.261
Oil[13]	0.28
District heating[12]	0.245

The emission factor used for electricity varies dependent on whether a Norwegian average or European average is used. The total GHG emissions for the different future scenarios analyzed in this thesis are calculated for all emission factors for electricity. This is done to see the importance of this factor.

[12] Source: (CICERO, 2012)
[13] Source: (Energilink, 2014)

4 Results and sensitivity analysis

When reading this chapter it is recommended to look at appendix B from time to time since this appendix give a short explanation of what is included in each renovation package. This will make it easier to connect the results up to the relevant renovation package.

4.1 Results from energy calculations before and after renovations

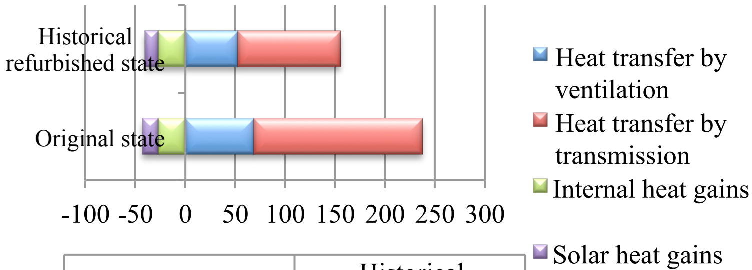
This chapter includes energy calculations for all building types before and after renovation. Subsection 4.1.1 describes the energy use for apartment blocks built before 1980 in both original and historical refurbished state. Subsection 4.1.2 shows the calculated heating effect and dimensioning sizes of different renovation components like heat pumps and solar collectors. The last subsection of this chapter, subsection 4.1.3, includes a review of the calculated energy demand after each of the renovation packages have been implemented to the buildings.

4.1.1 Energy use before renovation

Three time periods have been analyzed, where the first one is before 1956, the second one between 1956 and 1970, and the last one between 1971 and 1980.

Energy use for apartment blocks built before 1956

These two types of apartment blocks built before 1956 have the properties given in Figure 13 when it comes to heat losses and heat gains. As the figure show losses due to transmission stand for the biggest amount, and improvement done to the building envelope should therefore be prioritized.



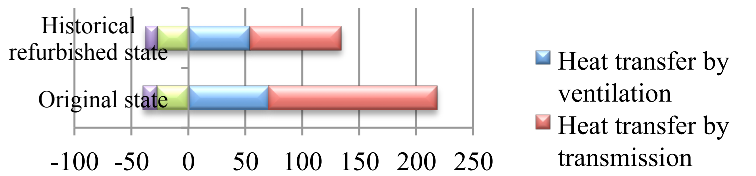
	Original state	Historical refurbished state
Heat transfer by ventilation	69	53
Heat transfer by transmission	168	102
Internal heat gains	-28	-28
Solar heat gains	-15	-13

Figure 13: Heat gains and heat losses for apartment blocks built before 1956 in original and historical refurbished state (kWh/m^2 BRA)

Since apartment blocks in original state have the highest transmission losses these building types should be refurbished first. Total delivered energy to space heating and domestic hot water before any new renovations are implemented are calculated to be 239 kWh/m^2 BRA and 153 kWh/m^2 BRA in original and historical refurbished state respectively.

Energy use for apartment blocks built between 1956 and 1970

Apartment blocks built between 1956 and 1970 have the properties shown in Figure 14 when it comes to heat losses and heat gains. As the figure show the transmission losses is highest for the building in original state due to higher U-values of the building envelope.



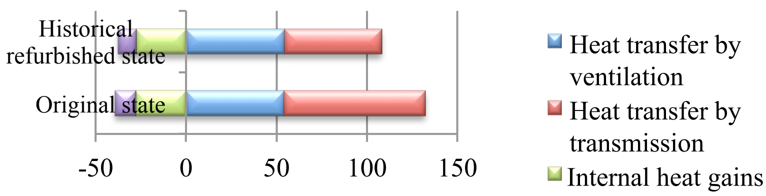
	Original state	Historical refurbished state
Heat transfer by ventilation	70	54
Heat transfer by transmission	148	80
Internal heat gains	-28	-28
Solar heat gains	-12	-10

Figure 14: Heat gains and heat losses for apartment blocks built between1956 and 1970 in original and historical refurbished state (kWh/m^2 BRA)

Due to improvements done on the external envelope for apartment blocks in historical refurbished state the transmission losses are approximately 70 kWh/m^{2}year smaller than for apartment blocks in original state, which is a major improvement. Total delivered energy to space heating and domestic hot water before any new renovations are implemented are 224 kWh/m^2 BRA and 133 kWh/m^2 BRA in original and historical refurbished state respectively.

Energy use for apartment blocks built between 1971 and 1980

Apartment blocks built between 1971 and 1980 have the properties shown in Figure 15 when it comes to heat losses and heat gains. When comparing this figure to Figure 13 and Figure 14 it is easy to see that the transmission losses are reduced significantly. In these apartment blocks heat loss due to ventilation and transmission are almost equivalent dominant. This means that improvements done on the building envelope and to the ventilation system are equally important.



	Original state	Historical refurbished state
Heat transfer by ventilation	54	55
Heat transfer by transmission	78	53
Internal heat gains	-28	-28
Solar heat gains	-12	-10

Figure 15: Heat gains and heat losses for apartment blocks built between1971 and 1980 in original and historical refurbished state (kWh/m^2 BRA)

When deciding which renovation packages to analyze in an LCC the properties of the buildings in original and historical refurbished state are of importance. The fourteen renovation packages analyzed in this thesis are chosen due to assumptions that these packages seems realistic economically and gives a reduction in net energy use. Total delivered energy to space heating and domestic hot water before any new renovations are implemented are 132 kWh/m^2 BRA and 106 kWh/m^2 BRA for apartments built between 1971 and1980 in original and historical refurbished state respectively.

Comparison to results from Enova

Enova have estimated a net energy demand for space heating as given in Table 27 for the different building typologies. However, Enova defines the standard dwellings as an average of dwellings in original state and dwellings in "historical refurbished"-state (see chapter 2.10.3)

Table 27: Comparison to numbers given by Enova (Prognosesenteret AS & Entelligens AS, 2012)

	Delivered energy to space heating (kWh/m^{2}year)			
	Original	Historical upgraded	Weighed average	Enova
Before 1956	200	118.4	132	159
1956-1970	183.7	99.2	120.3	139
1971-1980	92.8	71.5	77	54.9

The differences between results in this report and the Enova report can be explained by inclusion of window replacement in the historical refurbishments in this report. In the Enova report the standard dwelling is defined as a weighted average between the dwelling in original state and the dwelling in historical refurbished state. 2.6 W/m^{2}K is therefore a weighed average of the window's U-value for the average building from this period (Prognosesenteret AS & Entelligens AS, 2012). If the U-value is kept equal to 2.6 W/m^{2}K in both original and historical refurbished state the weighed average is calculated to be 142 kWh/m^{2}year, which is more similar to what Enova calculated. Reasons for this error can be explained by slightly different thermal bridge values and air infiltration values as well as different heating system. The values for thermal bridge and air infiltration in this report are based on standard values given by TABULA (Loga & Diefenbach, 2012).

It can be discussed whether it was a good choice to use average U-values for windows from the Enova report as those values did not give a correct picture of the U-value in a typical building in original state and a typical building in historical refurbished state. The U-value of the original window is probably a bit higher than 2.6 W/m^{2}K, maybe around 4 W/m^{2}K. Since TEK87 require a U-value lower than 2.4 W/m^{2}K and TEK97 require a U-value lower than 1.6 W/m^{2}K (see Table 4) it is probably a good estimate to set the average U-value after historical refurbishment equal to 2.0 W/m^{2}K for the two first building typologies.

The weighed average for apartments built between 1971 and 1980 is calculated to be 77 kWh/m^{2}year, which is about 22.1 kWh/m^{2}year higher than the value given by Enova (Prognosesenteret AS & Entelligens AS, 2012). This error can be explained by slightly different parameter values. Since the average air change rate during heating season related to the utilization of the building is based on average values given in TABULA this can result in slightly different values of this energy flow. Average values for combination of heating sources are also used in the Enova report, which means that the “typical” building is estimated to use 5 different heating sources, where one of them are heat pumps. Including use of heat pumps can lower the net energy need and can therefore explain the differences between the results given in this report and the results given in the Enova report (Prognosesenteret AS & Entelligens AS, 2012).

4.1.2 Dimensioning of components connected to the heating system

This subsection includes dimensioning of heat pumps, solar collectors, heat exchangers for district heating and electric boilers since these measures are included in some of the renovation packages.

4.1.2.1 Dimensioning of heat pumps

Installation of heat pumps is included in renovation package 4, 6, 9 and 13. The necessary dimensioning heating effect of the heat pumps varies in the different renovation packages due to different heating demand. To calculate the heating effect it is necessary to know the heat transfer coefficient due to ventilation (H_{ve}) and the heat transfer coefficient due to transmission (H_{tr}), and these values for each of the renovation packages are given in Table 28.

Table 28: Heat transfer coefficient for renovation package 4, 6, 9 and 13

	Renovation package	Built before 1956		Built between 1956 and 1970		Built between 1971 and 1980	
		Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
H_{tr} (W/K)[14]	4	828.1	514.6	1364.3	735.6	1042.9	886.5
	6	302.48	302.48	486	486	692.3	692.3
	9	190.4	190.4	304	304	430.4	430.4
	13	190.4	190.4	304	304	430.4	430.4
H_{ve}(W/K)[14]	4	386.24	289.68	718.08	538.56	918	918
	6	241.4	241.4	448.8	448.8	765	765
	9	217.3	217.3	403.9	403.9	688.5	688.5
	13	217.3	217.3	403.9	403.9	688.5	688.5

The heat transfer coefficients have the same values for buildings in original state and historical refurbished state for all renovation packages except renovation package 4 (see Table 28). This is because these renovation packages includes a TEK10 or passive house upgrade of the building envelope in addition to the heat pump, which implies that both original and historical refurbished buildings are upgraded to the same quality. Since renovation package 13 includes an air-to-water heat pump the domestic hot water need also should be included. The heating effect for domestic hot water is set to be 5.1 W/m^2 heated floor area (NS3031, 2011). The required indoor temperature (T_{in}) is set to be 20.39 ℃ for all building types, and the dimensioning outdoor temperature (DOT) is set to be -20.4 ℃ (Arnstad, 2004). Using Equation 5 (see page 51) for renovation package 4, 6 and 9, and Equation 6 (see page 52) for renovation package 13 gives the required dimensioning given in Table 29.

[14] Calculated from the energy balance model – see attachment D1

Table 29: Dimensioning heating effect for heat pumps (see appendix D2)

	Renovation package	Built before 1956		Built between 1956 and 1970		Built between 1971 and 1980	
		Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
$P_{dim,whole\ building}$ (kW)	**4**	29.72	19.7	50.96	31.2	48	44.2
	6	13.31	13.31	22.88	22.88	35.67	35.67
	9	9.98	9.98	17.33	17.33	27.38	27.38
	13	12	12	21	21	33	33

By using this dimensioned heating effect for the apartment blocks it is possible to estimate how many heat pumps of size 3 kW and 4 kW that is required for renovation package 4, 6 and 9, and how many heat pumps of size 6 kW that is required for renovation package 13 (see Table 30).

Table 30: Number of heat pumps required for each building types

	Renovation package	Built before 1956		Built between 1956 and 1970		Built between 1971 and 1980	
		Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
Number of heat pumps with capacity 3 KW[15]	**4**	-	7	-	11	16	15
	6	5	5	8	8	12	12
	9	4	4	6	6	10	10
Number of heat pumps with capacity 4 KW[15]	**4**	8	-	13	-	-	-
	6	-	-	-	-	-	-
	9	-	-	-	-	-	-
Number of heat pumps with capacity 6 KW[16]	**13**	2	2	4	4	6	6

Using these results together with the cost information given in chapter 3.2.3.2 and 3.2.3.3 gives a total investment cost for heat pumps per m^2 heated floor area as given in Table 31.

Table 31: Total investment cost for heat pumps for renovation package 4, 6, 9 and 13

	Renovation package	Built before 1956		Built between 1956 and 1970		Built between 1971 and 1980	
		Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
Investment cost (NOK/m^2 BRA)	**4**	464	313	313	265	226	212
	6	224	224	192	192	169	169
	9	179	179	144	144	141	141
	13	313	313	337	337	297	297

[15] Air-to-air heat pumps
[16] Air to-water heat pumps

4.1.2.2 Dimensioning of solar collectors

Renovation package 12 and 14 includes installation of solar collectors. In addition to this both renovation packages also includes a passive house envelope upgrade. The difference between the two packages is that renovation package 14 also includes installation of a balanced ventilation system with heat recovery. Because of the heat recovery unit the required size is reduced. As mentioned in chapter 3.2.3.5 (see page 54) the solar collectors should be dimensioned to cover 60 % of the heating demand (Andersen I., 2008). The calculated yearly production capacity for the solar collectors and the necessary dimensioning is calculated to be as given in Table 32 and Table 33.

Table 32: Characteristics for solar collectors – ren.12

	Built before 1956	Built between 1956 and 1970	Built between 1971 and 1980
Necessary yearly production from the solar collectors (kWh/year)	24 020.3	43 372.4	69 038
Number of solar collectors with a capacity of 6548 kWh/year	3	6	10
Number of solar collectors with a capacity of 3274 kWh/year	2	2	2
Total investment cost (NOK/m^2 BRA)	1 183	1 104	1014

Table 33: Characteristics for solar collectors -ren.14

	Built before 1956	Built between 1956 and 1970	Built between 1971 and 1980
Necessary yearly production from the solar collectors (kWh/year)	13 900	24 105	40 133
Number of solar collectors with a capacity of 6548 kWh/year	2	3	6
Number of solar collectors with a capacity of 3274 kWh/year	1	2	1
Total investment cost (NOK/m^2 BRA)	737	636	599

Comparing Table 33 and Table 32 shows that the investment cost connected to installation of solar collectors decrease when including installation of a balanced ventilation system with heat recovery. However, it is not enough to cover the extra cost connected to installation of a balanced ventilation system with heat recovery.

4.1.2.3 *Dimensioning of heat exchangers for district heating*

Installation of heat exchangers for connection to the district heating grid is included in renovation package 8 and 11. The necessary dimensioning heating effect for the heat exchangers varies in the different renovation packages due to different heating demand. To calculate the heating effect it is necessary to know the heat transfer coefficient due to ventilation (H_{ve}) and the heat transfer coefficient due to transmission (H_{tr}), and these values for each of the renovation packages are given in Table 34.

Table 34: Heat transfer coefficient for renovation package 8 and 11

	Renovation package	Built before 1956	Built between 1956 and 1970	Built between 1971 and 1980
H_{ve} (W/K)[17]	8	241.4	448.8	765
	11	217.26	403.92	688.5
H_{tr}(W/K)[17]	8	302.48	486	692.3
	11	190.41	304.01	430.4

When using district heating as the heating source it is not necessary to use another heating source to cover the peak loads, and district heating has therefore the ability to cover the entire heating demand for space heating and domestic hot water. The heating effect for domestic hot water is set to be 5.1 W/m^2 heated floor area (NS3031, 2011). Using Equation 7 together with the indoor temperature and dimensioning outdoor temperature as given in subsection 4.1.2.1 gives a dimensioning heating effect for the heat exchangers as given in Table 35.

Table 35: Dimensioning heating effect for heat exchangers, ren. 8 and 11

	Renovation package	Built before 1956	Built between 1956 and 1970	Built between 1971 and 1980
$P_{heat\ exchanger}$ (kW)	8	25.08	43.51	68.62
	11	217.26	403.92	688.5

4.1.2.4 *Dimensioning of electrical boilers*

Installation of an electric boiler is included as peak load in renovation package 12, 13 and 14, and is dimensioned to be the same in all of these renovation packages since all of them include a passive house upgrade of the building envelope (see Table 36).

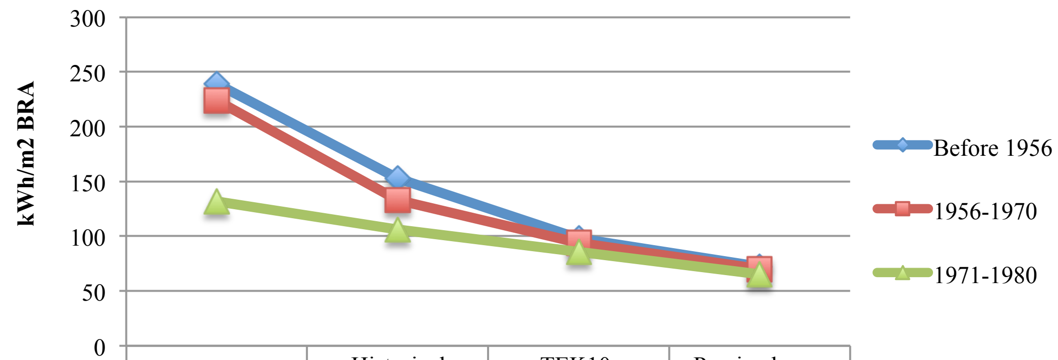
Table 36: Calculation of required heating effect for electric boiler

	Built before 1956	Built between 1956 and 1970	Built between 1971 and 1980
H_{ve} (W/K)[17]	217.26	403.92	688.5
H_{tr}(W/K)[17]	190.41	304.01	430.4
T_{in}(°C)[18]	20.39	20.39	20.39
DOT(°C)	-20.4	-20.4	-20.4
$P_{heat\ exchanger}$(kW)	19.53	34.26	54.82
Investment cost (NOK/m^2 BRA)	32	30	28

[17] Calculated from the energy balance model – see attachment D1
[18] Number gotten from: (Prognosesenteret AS & Entelligens AS, 2012)

4.1.3 Energy use after different renovation packages

Energy savings due to envelope upgrades are shown in Figure 16, and describes the energy reduction potential of renovation package 2 (TEK10 upgrade) and 3 (passive house upgrade).



	Original	Historical refurbishment	TEK10-refurbishment	Passive house refurbishment
Before 1956	239	153	97.8	72
1956-1970	224	133	93.6	70.2
1971-1980	132	106	85.9	65.3

Figure 16: Energy delivered to space heating and domestic hot water in original state, historical refurbished state, and after TEK10- and passive house refurbishment (kWh/m^{2}year)

After a TEK10-refurbishment is applied to the building's thermal envelope, resulting in U-values that fulfill the technical regulations, the total energy delivered to space heating is estimated to decrease with 68 % for the two oldest building typologies. If a passive house refurbishment is applied an energy saving of 81 % is possible (see Figure 16). This means that the annual energy need for space heating for a typical apartment block built before 1956 can be reduced from 200 kWh/m^2 to 38 kWh/m^2. The reduction potential for the two oldest building typologies are similar, as seen in Table 37, but for apartment blocks built in the period 1971-1980 the net energy need for space heating is considerably lower in original state as a consequence of much lower U-values for the building envelope. The building envelope has also become more compact which makes it more energy efficient. From being an apartment block that consisted of 8 apartments in 1956, the typical apartment block from this period consists of 24 apartments, but still have the same number of floors. In original state the annual energy use for space heating is calculated to be 92.8 kWh/m^2. For buildings built during the time period 1956-1970 the net annual energy need for space heating is calculated to be 192.5 kWh/m^2. This improved development of building typology can be explained by new building regulations in 1969 that had stricter regulations when it came to the quality of the building envelope (dsb, 1969)

Table 37: Annual energy savings from original state (kWh/m^{2}year)

	Annual savings from original state (kWh/m^{2}year)	
	TEK10-refurbishment package	Passive house refurbishment package
Before 1956	136.2	162
1956-1970	124.1	147.5
1971-1980	40.9	61.5

Since most of the apartment blocks from these periods are in historical refurbished state (see Figure 3 in chapter 2.4) a more realistic reduction potential is from historical refurbished state to TEK10- or passive house-state, which corresponds to an annual energy reduction of 54.6 kWh/m^2 or 80.4 kWh/m^2 respectively for apartments block built before 1956 (see Figure 16).

Table 38: Annual energy savings from historical state (kWh/m^2year)

	Annual savings from historical refurbished state (kWh/m^2year)	
	TEK10-refurbishment package	Passive house refurbishment package
Before 1956	54.6	80.4
1956-1970	39.6	63
1971-1980	19.6	40.2

Introducing other supplementary refurbishment measures like installation of heat pumps or balanced ventilation systems with heat recovery reduces the energy need further. Table 39 shows the delivered energy to space heating and domestic hot water after each of the renovation packages analyzed in this project. Renovation package 0 is defined as the reference case and the energy reduction potential for the other renovation packages are compared with this reference case. All values in Table 39 are given in kWh/m^2 heated floor area per year.

Table 39: Delivered energy to space heating and domestic hot water after renovation (kWh/m^2 year)

Renovation package		Before 1956		Between 1956-1970		Between 1971-1980	
		Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
0	Electricity	192	128.1	182.8	113.1	104	95.1
	Wood	26.6	16.3	25	13.7	11.3	10.6
1	Electricity	178.9	114.1	173.0	102.4	93.2	84.2
	Wood	24.3	13.9	23.3	11.9	9.4	8.7
2	Electricity	88.7	88.7	84.9	84.9	78.5	78.5
	Wood	9.5	9.5	8.8	8.8	7.7	7.7
3	Electricity	66.8	66.8	65	65	60.9	60.9
	Wood	5.7	5.7	5.4	5.4	4.7	4.7
4	Electricity	126.8	95.1	121.6	87.1	76.3	70.0
	Wood	0	0	0	0	0	0
5	Electricity	151.8	97.2	141.5	81.4	72.2	62.9
	Wood	19.6	11.0	17.8	8.2	5.8	5.0
6	Electricity	65.4	65.4	63.2	63.2	59.5	59.5
	Wood	0	0	0	0	0	0
7	Electricity	62.6	62.6	58.2	58.2	51.5	51.5
	Wood	5.0	5.0	4.2	4.2	3.0	3.0
8	Electricity	0	0	0	0	0	0
	District heating	102,1	102.1	97.7	97.7	90.1	90.1
9	Electricity	52.9	52.9	51.8	51.8	49.5	49.5
	Wood	0	0	0	0	0	0
10	Electricity	40.1	40.1	37.6	37.6	36.8	36.8
	Wood	1.1	1.1	0.6	0.6	0.5	0.5
11	Electricity	0	0	0	0	0	0

	District heating	76.4	76.4	74.3	74.3	69.5	69.5
12	Electricity	29.9	29.9	29.1	29.1	27.3	27.3
	Wood	0	0	0	0	0	0
13	Electricity	38.6	38.6	37.6	37.6	35.2	35.2
	Wood	0	0	0	0	0	0
14	Electricity	18.0	18.0	16.9	16.9	16.6	16.6
	Wood	0	0	0	0	0	0

Renovation package 0 (no other energy related upgrades than minor window improvements) is seen as the minimum renovation measure that is required, and the energy use after this renovation package is therefore high (marked red). The four renovation packages that lead to the highest energy reduction is marked with green, hence renovation package 10, 12, 13 and 14. Renovation package 10 includes a passive house upgrade of the building envelope, combined with installation of a balanced ventilation system. Implementation of this renovation package leads to a reduction in space heating demand, so that the passive house requirement of a delivered energy to space heating below 15 kWh/m^{2}year is fulfilled (NS3700, 2013). It also gives a satisfying air quality in the building. It is general recommended to have a balanced ventilation system installed in passive houses due to the tight building envelope (Thomsen & Berge, 2012). Renovation package 12 includes a passive house upgrade of the building envelope combined with installation of solar collectors. Since the solar collector can cover 60 % of the space heating and domestic hot water demand the need for electricity from the grid is low, hence giving a low external heating demand. Renovation package 14 is similar to renovation package 12, but includes installation of a balanced ventilation system, which reduces the net energy need further. Renovation package 13 includes a passive house envelope upgrade and installation of a air-to-water heat pump, that covers 90 % of the heating demand for space heating and domestic hot water, and therefore gives a low net heating demand.

The results general show that it is beneficial to first upgrade the building envelope to either TEK10 or passive house level. Renovation package 4 and 5, which only includes installation of air-to-air heat pumps and balanced ventilation system, respectively, will not give a high enough reduction in energy use.

4.2 NPV results for the different renovation packages

For simplification the different building types are called building type 1a, 1b, 2a, 2b etc., and the explanation of each building type is given in Table 40.

Table 40: Description of building types

Building type 1a	Apartment blocks built before 1956 in original state (see page 43)
Building type 1b	Apartment blocks built before 1956 in historical refurbished state (see page 43)
Building type 2a	Apartments blocks built between 1956 and 1970 in original state (see page 43)
Building type 2b	Apartment blocks built between 1956 and 1970 in historical refurbished state (see page 44)
Building type 3a	Apartments blocks built between 1971 and 1980 in original state (see page 44)
Building type 3c	Apartment blocks built between 1971 and 1980 in historical refurbished state (see page 44)

The calculated NPV savings (without any subsides from Enova) for all the renovation packages analyzed in this study compared to base case (renovation package 0), who has a calculated NPV of 4 323, 3 210, 3 996, 2 780, 2 590 and 2 442 NOK/m^2 heated floor area for building type 1a, 1b, 2a, 2b, 3a and 3b respectively, is given in Figure 17.

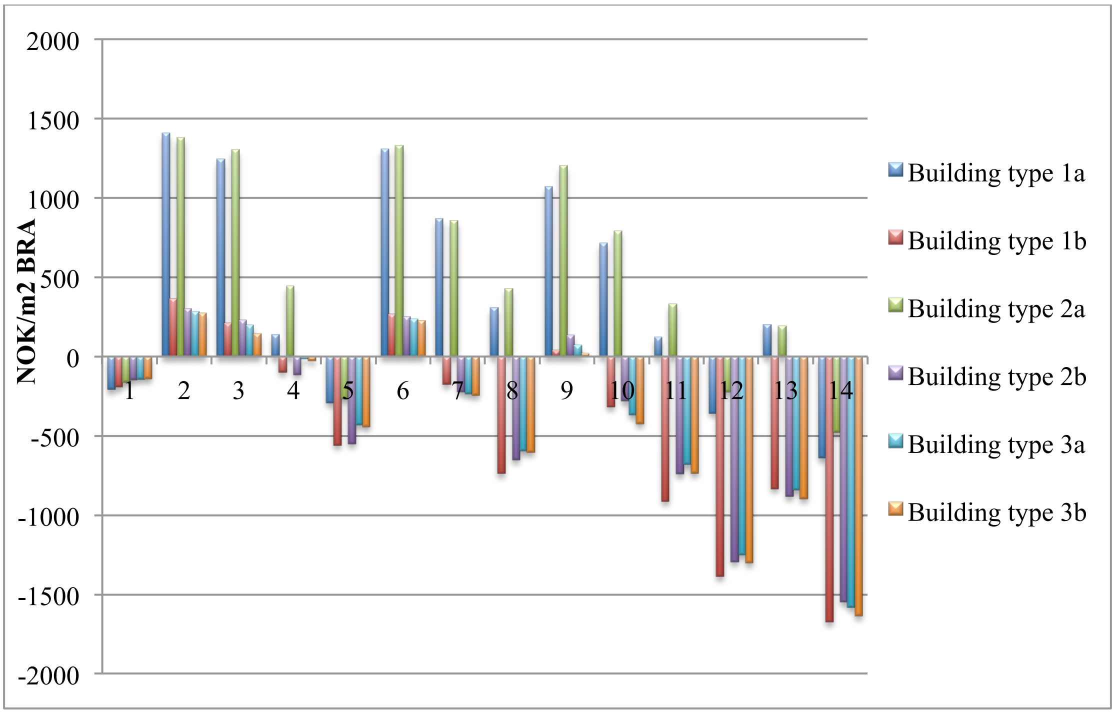


Figure 17: NPV savings (without Enova subsides) from base case (renovation package 0) (see appendix D2)

As shown in the figure almost all renovation packages except of renovation package 1 (upgrading the windows to passive house standard), renovation 5 (installing a balanced ventilation system with heat recovery), renovation package 12 (upgrading the building envelope to passive house level and installing a water-based heating system that is connected to a solar collector system) and renovation package 14 (equal to renovation package 12 but includes a balanced ventilation system as well) are economically beneficial to implement for building type 1a and 2a. The results generally show that it is very expensive to install a water-based heating system and a balanced ventilation system with heat recovery. Even though the energy savings by using solar collectors or air-to-water heat pumps are very good, the investment costs connected to these measures are too large, especially when the buildings don't have a water-based heating system installed already. If all the buildings were constructed with a water-based heating system originally renovation package 8, 11, 12, 13 and 14 would have a lower net present value and have a better chance in becoming economical efficient. To see the effect of changing this parameter a sensitivity analysis is performed and can be found in chapter 4.2.2.1.

It must be mentioned that it is a bit odd that the net present value of upgrading the windows to passive house level (renovation package 1) gives a negative profitability over a period of 36 years. Similar study from Asplan Viak shows that upgrading the windows to passive house level generally is profitable (up to 112 NOK/m^2 when upgrading the U-value from 1.6 W/m^2K to 0.8 W/m^2K) (Førland-Larsen, 2012). However, the investment cost connected to passive house windows are set to be up to 3 times as high as the window price used in the Asplan Viak report, which may explain the difference. Reducing this cost parameter will most likely make this energy efficiency measure profitable.

The results generally show that most of the renovation packages are beneficial for the building types that have high heat consumption before renovation (refers to building type 1a and 2a). For the other building types only renovation package 2 (TEK10-upgrade of the building envelope), 3 (passive house upgrade of the building envelope), 6 (TEK10 upgrade of the building envelope + installation of air-to-air heat pump) and 9 (passive house upgrade of the building envelope + installation of air-to-air heat pump) are profitable over a period of 36 years. It must though be mentioned that upgrading the building envelope to a passive house level general requires installation of a balanced ventilation system to achieve a good indoor environment (Thomsen & Berge, 2012), so renovation package 3 and 9 are somewhat unrealistic. However, since re-installation costs connected to exhaust ventilation is not included in the other packages, the extra cost by installing a balanced ventilation system is a bit higher than it should be. The cost connected to re-installing an exhaust ventilation system is though quite low (Sætra, 2014) so it is anticipated that this assumption won't have a too large impact on the result. Reducing the costs connected to installing a balanced ventilation system will though have an impact on the result, and a sensitivity analysis on this parameter is therefore done (see chapter 4.2.2.5).

As shown in Figure 17, installation of solar collectors (renovation package 12 and 14) is the least beneficial measure, mainly because of very high investment costs connected to the solar collector system and the water-based heating system. The delivered energy to space heating and domestic hot water after implementation of this renovation package is very low, which makes this package very dependent on the electricity price to be beneficial. Because of many sensitive parameters a sensitivity analysis of several parameters are done especially for this renovation package to see what is required to make it beneficial (see chapter 4.2.2.4).

It must be mentioned that achieving an energy level that satisfy TEK10 (annual delivered energy of 115 kWh/m^2 for apartment blocks) (Kommunal- og regionaldepartementet, 2010) is difficult without installing a heat pump or a balanced ventilation system with heat recovery. The same is the case when trying to reach the passive house requirement of a space heating demand below 15 kWh/m^2.

4.2.1 The effect of Enova subsides

Adding subsides from Enova into the NPV calculations have little impact on the overall result. Some renovation packages become more profitable, but the support amount is not high enough to make all renovation packages profitable. Renovation package 7 (TEK10 envelope upgrade + installation of balanced ventilation system) and 10 (Passive house envelope upgrade + installation of balanced ventilation system), though, becomes almost efficient for all building types after receiving Enova support (see Figure 18). This means that getting support from Enova promotes installation of balanced ventilation system with heat recovery, which has a good impact on the indoor environment as well as the required net energy demand.

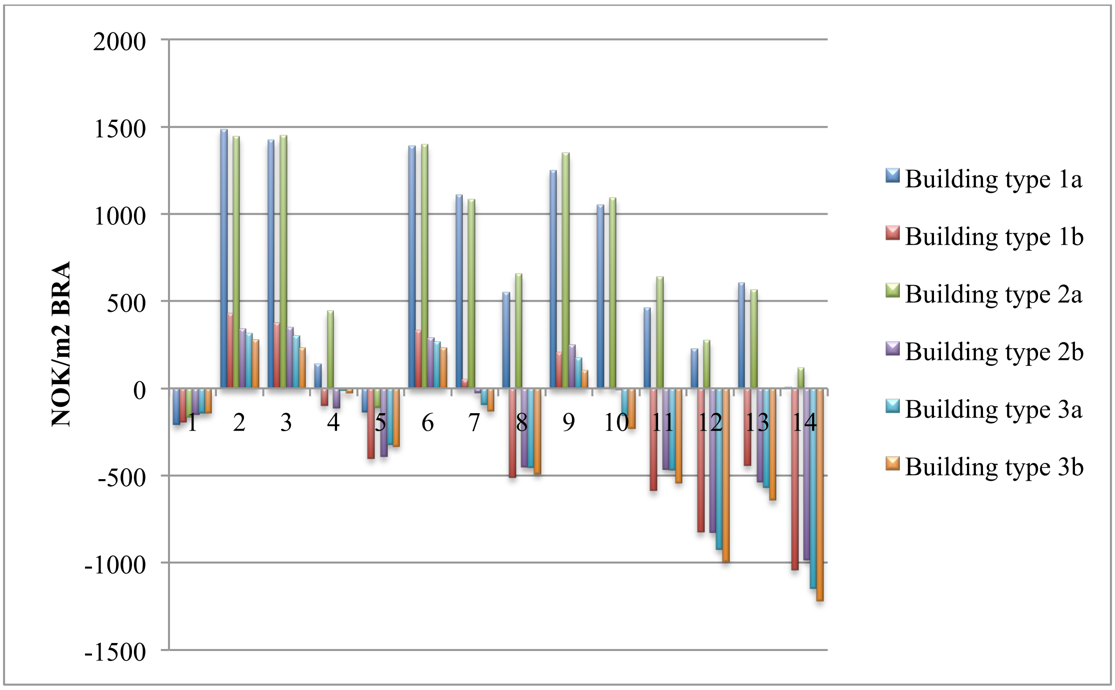


Figure 18: NPV savings (with subsides) from base case (renovation package 0)

Renovation package 12 (Passive house envelope upgrade + installation of solar collectors) also becomes profitable for building type 1a and 2a after adding subsides from Enova. This shows that it is beneficial to get support from Enova even though it is not enough to make all refurbishment profitable for all building types.

There are, though, some uncertainties connected to the support amount that is possible to get from Enova, and it is therefore decided to not include these subsides in the other sensitivity analyzes. By doing this it is easier to see what is required of other actions to make the renovation packages with negative NPV value profitable.

4.2.2 Sensitivity analysis on different cost parameters

This chapter includes several sensitivity analyzes to show the impact of several cost parameters. Chapter 4.2.2.1 shows the impact of having a water-based heating system installed before renovation. The impact of a higher electricity price and a higher or lower discount rate is discussed in chapter 4.2.2.2 and 4.2.2.3 respectively, while chapter 4.2.2.4 gives a sensitivity analysis on the investment cost of installing a solar collector system to see how low this cost has to be to make this an efficient solution. The same is done for the investment cost for a balanced ventilation system with heat recovery (see chapter 4.2.2.5).

4.2.2.1 The benefits of having a water-based heating system installed before renovation

To see the impact of installing a water-based heating system with radiators when it comes to total profitability for several renovation packages, an analysis is completed to see what happens if it is assumed that a water-based heating system is installed in the building originally. In Figure 19 "a" stands for the case where the buildings don't have installed a water-based system originally, and "b" stands for the case where it is assumed that the buildings have installed a water-based heating system originally.

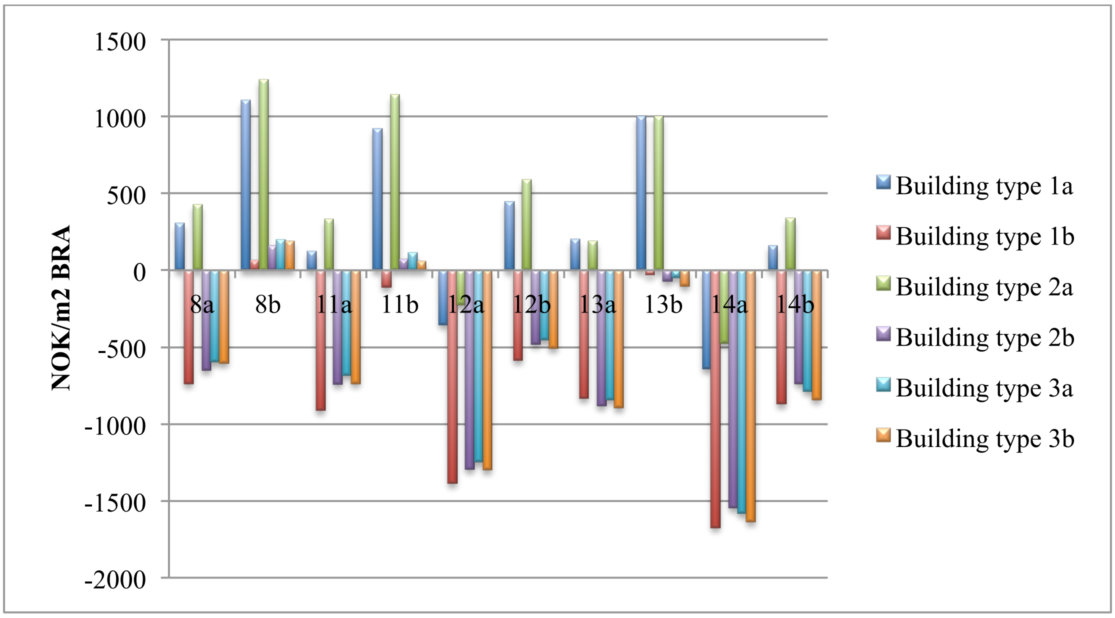


Figure 19: The effect of having a water-based heating system installed before renovation

As the figure shows renovation package 8 (TEK10 envelope upgrade + changing to district heating) and 11 (passive house envelope upgrade + changing to district heating) becomes beneficial for just about every building type if a water-based system is installed in the buildings originally. When it comes to investing in a solar collector system combined with a passive house envelope upgrade (12 and 14) this system solution only becomes efficient for the two building types with the highest energy consumption before renovation (building type 1a and 2a). However, the negative cost for the other building types decreases significantly. Installing an air-to-water heat pump combined with a passive house envelope upgrade (13) becomes more beneficial for building type 1a and 2a, and almost beneficial for the other building types. With a longer calculation period, for instance up to 2060, this renovation package would probably be economical efficient for all building types if a water-based heating system was installed in the buildings originally.

4.2.2.2 The impact of a higher electricity price

Since the cost-benefits by introducing measures that lead to a lower electricity consumption is dependent on the electricity price a sensitivity analysis on this parameter is completed. Increasing the electricity price with 50 % gives NPV savings from base case as given in Figure 20.

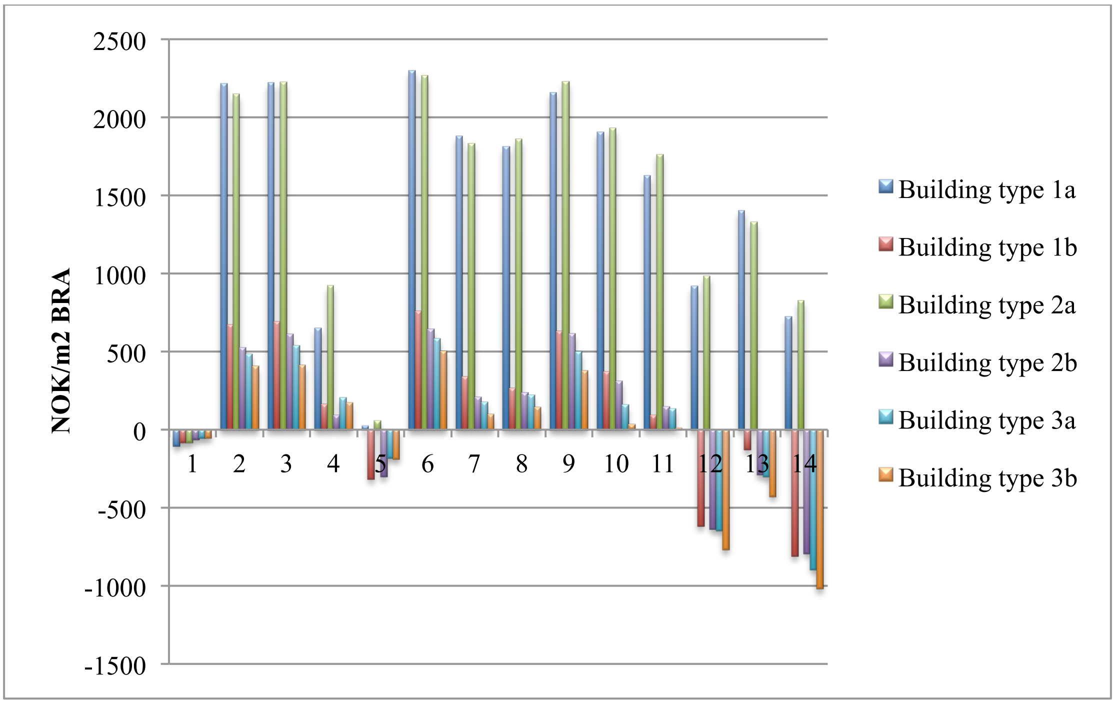


Figure 20: NPV savings (without Enova subsides) from base case with a 50 % higher electricity price

When increasing the electricity price with 50 %, which means increasing the price from 0.893 NOK/kWh to 1.34 NOK/kWh most of the measures become profitable for all the building types. However, renovation package 12, 13 and 14, which includes installation of water-based heating system, solar collectors and/or air-to-water heat pumps do not become economically efficient for building type 1b, 2b, 3a and 3b. This is because the energy use for these building types originally is relatively low, and the investment cost of the renovation measures is very high. A higher electricity price will therefore have most impact when the energy reduction is high. For the building types that have very high electricity consumption originally the energy reduction potential is highest, and therefore are these buildings also most sensitive for the electricity price.

Comparing Figure 20 to Figure 17 (see page 69) shows that increasing the electricity price with 50 % makes renovation package 7 (TEK10 envelope upgrade + installation of balanced ventilation system with 70 % heat recovery), 8 (TEK10 envelope upgrade + connecting to district heating), 10 (Passive house envelope upgrade + installation of balanced ventilation system with 80 % heat recovery) and 11 (Passive house envelope upgrade + connecting to district heating) profitable for all building types analyzed in this thesis. The other renovation packages that have negative NPV difference from base case also become less negative, which implies that an increase in the electricity price is efficient for making renovation projects profitable.

4.2.2.3 *The impact of a lower or higher discount rate*

To see the impact of the discount rate one lower discount rate of 2 % and one higher of 7 % based on factors used in other studies are used (Førland-Larsen, 2012).

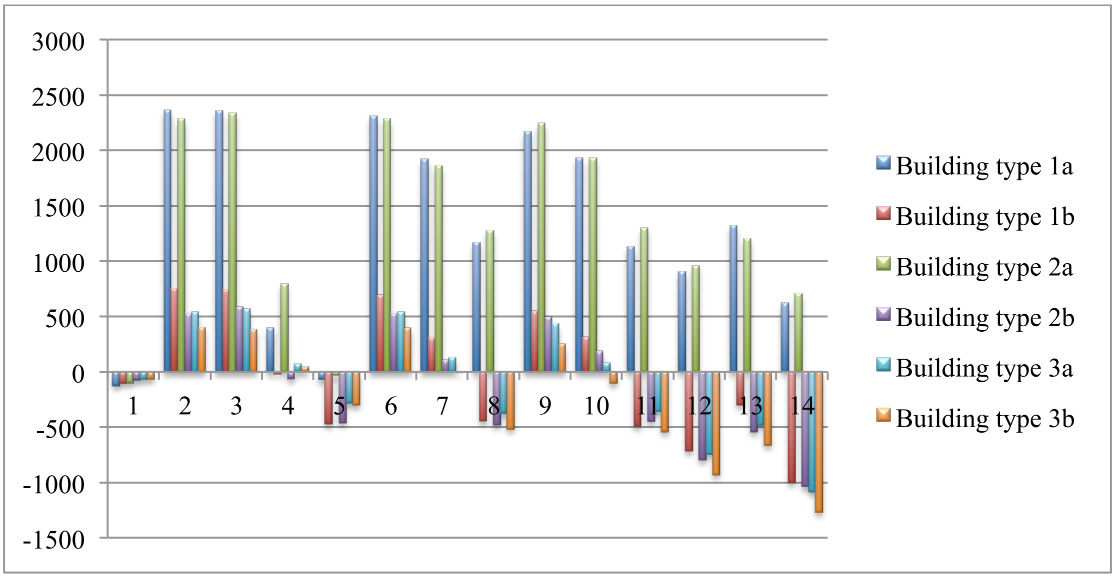


Figure 21: NPV savings from base case when using a discount rate of 2 %

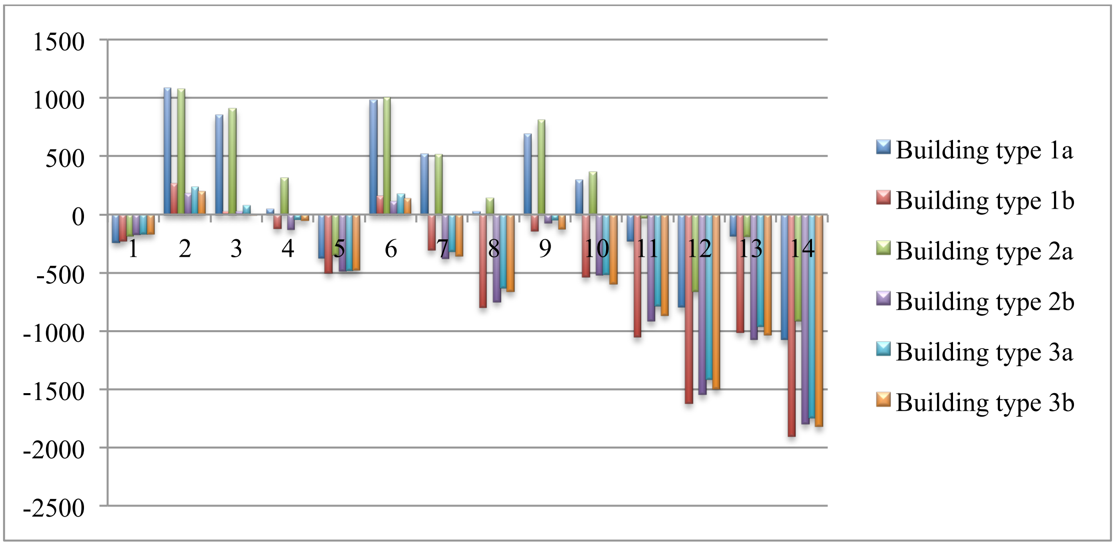


Figure 22: NPV savings from base case when using a discount rate of 7 %

As shown in Figure 21 and Figure 22 the discount rate has a huge impact on the result. A low discount rate general makes renovation measures with a high energy reduction potential more efficient, while a high discount rate is very dependent on the investment cost in the first years of the study and the impact of energy savings is therefore not as big. Using a discount rate of 2 % makes all renovation packages efficient for building type 1a and 2a, since these building types have high energy requirements before renovation. Renovation package 10 (passive house envelope upgrade combined with installation of a balanced ventilation system with heat recovery) general gets efficient for all building types when reducing the discount rate from 5 % to 2 %, which makes this renovation package more attractive. The result from the sensitivity analysis general shows that the discount rate should be as low as possible to promote energy efficiency measures with a huge energy saving potential, but that has somewhat high investment costs.

4.2.2.4 Sensitivity analysis of the investment cost for a solar collector system

This sensitivity analysis is based on renovation package 12 and 14, which includes passive house envelope upgrades as well. Renovation package 14 also includes installation of a balanced ventilation system, but this cost is remained constant in this sensitivity analysis. A sensitivity analysis of this parameter is though carried out in chapter 4.2.2.5.

The investment cost of a solar collector system is, as mentioned at page 64, quite high and depends on the required size. For renovation package 14 the size of the solar collectors is dimensioned to be smaller because of the additional installation of a balanced ventilation system with heat recovery (see page 64). As mentioned earlier a passive house envelope upgrade general requires installation of a balanced ventilation system to ensure a good indoor air quality. Not choosing to install a balanced ventilation system in a renovation project can lead to moisture damage and poor indoor air quality (Thomsen & Berge, 2012). This makes renovation package 12 a bit unrealistic. However, this renovation package is included to see how much more economically beneficial it is to install a solar collector system in a building if the installation cost of a balanced ventilation system is removed. Including a balanced ventilation system with heat recovery will, as shown in Table 33, decrease the investment cost of installing a solar collector, but not enough to cover the extra cost connected to installation of a balanced ventilation system.

The sensitivity analysis is performed by gradually decreasing the investment cost per produced kWh heat from the solar collector. The results are shown in Figure 23.

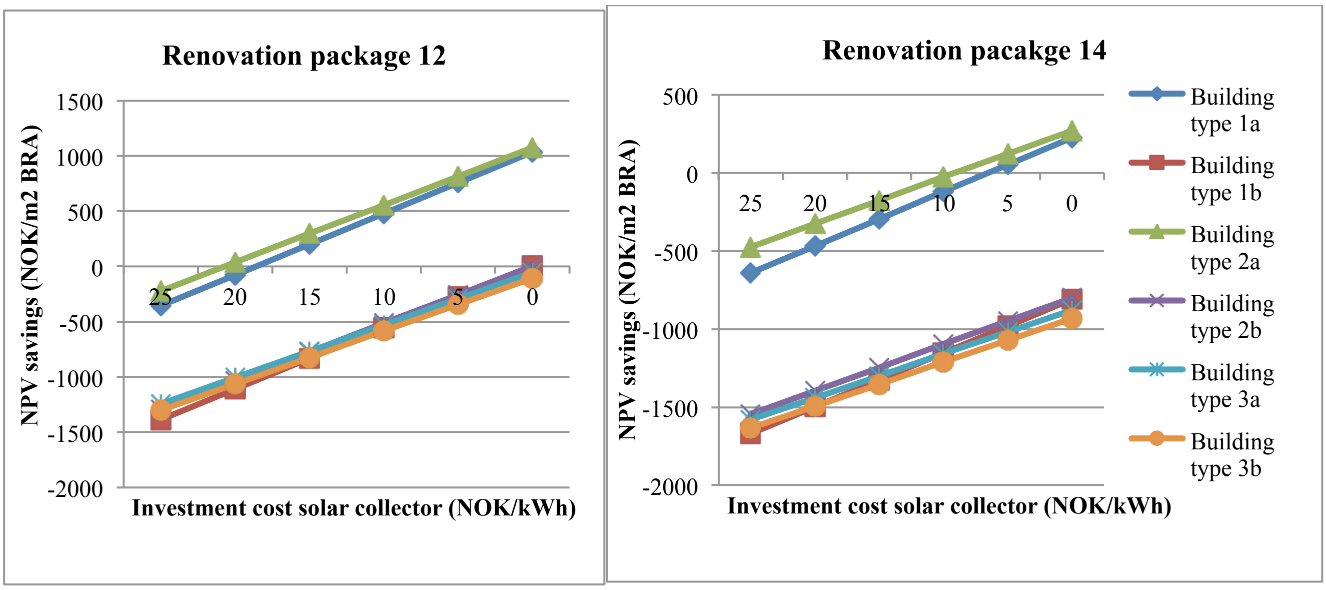


Figure 23: Sensitivity analysis on the solar collector cost parameter (not installed water-based heating system originally)

The investment cost per kWh produced heat has to be reduced down to 16.4 NOK/kWh for renovation package 12 and down to 8.5 NOK/kWh for renovation package 14 for building type 1a. A similar reduction is required for building type 2a. For the other building types that have a lower energy use originally, installing a solar collector system is not profitable over a period of 36 years no matter how much the cost gets reduced when a water-based heating system is not installed in the building originally. If a water-based heating system is installed in the building originally, the renovation packages becomes efficient at a higher unit cost (see Figure 24).

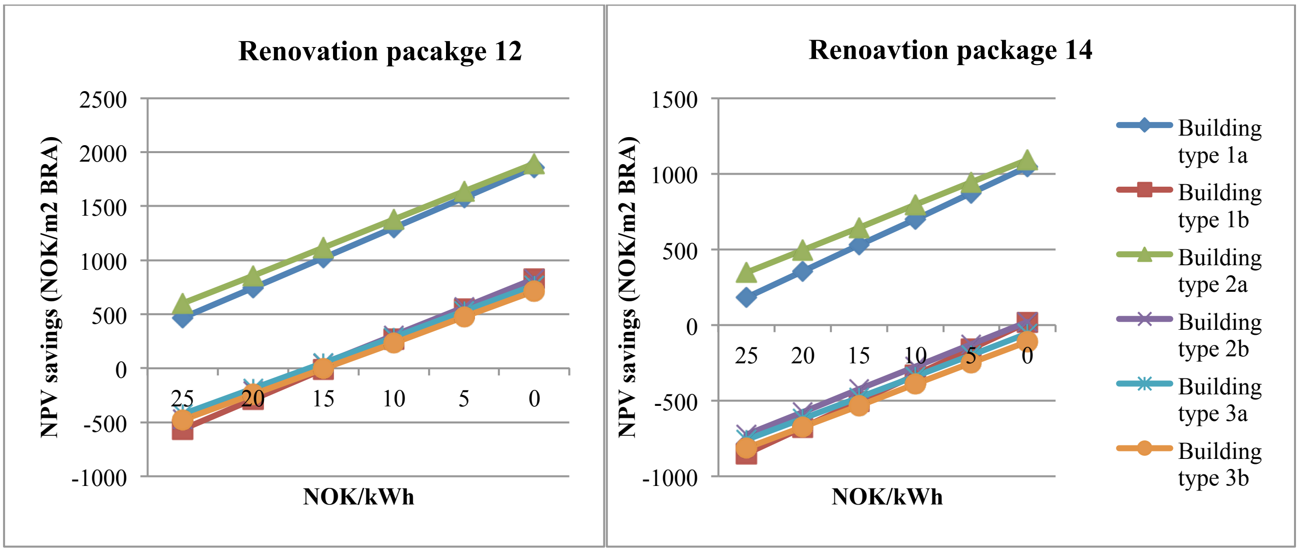


Figure 24: Sensitivity analysis on the solar collector cost parameter (installed water-based heating system originally)

The investment cost of the solar collector system can be much higher and still be profitable over a 36 years period when a water-based heating system is installed in the building originally. Including installation of a balanced ventilation system with heat recovery (renovation package 14) is beneficial for building type 1a and 2a for all price parameters given in the sensitivity analysis. But for the other building types this renovation package only becomes barely efficient when the investment cost of the solar collector system reach zero, which is very unlikely. It is therefore necessary to reduce the investment cost of several measures in this package to make it efficient for building types that have relatively moderate or low energy use originally.

4.2.2.5 Sensitivity analysis of the investment cost for a balanced ventilation system

The results given in Figure 17 in chapter 4.2 shows that renovation package 7 (TEK10 envelope upgrade + installation of a balanced ventilation system with 70 % heat recovery) and renovation package 10 (TEK10 envelope upgrade + installation of a balanced ventilation system with 80 % heat recovery) is beneficial for building type 1a and 2a since these building types have a very high energy use originally. For the other building types the renovation package is not beneficial over a period of 36 years when using an investment cost of 790 NOK/m^2 heated floor area for installation of a balanced ventilation system (Jensen & Rudén, 2013). To make these packages profitable for all building types analyzed in this project it is necessary to reduce the investment cost. It is therefore carried out a sensitivity analysis to see the necessary reduction of this cost parameter in order to make the renovation packages beneficial, and the results can be seen in Figure 25. It must be mentioned though that there are high willingness to pay for comfort, and all new dwellings built after TEK10 standard or passive house standard are constructed with a balanced ventilation system with heat recovery (Holøs, Maltha, & Berge, 2013).

Renovation package 7 is, as mentioned over, profitable for building type 1a and 2a. But if the investment cost of a balanced ventilation system is reduced with more than 17 % it also becomes economically efficient for building type 1b as well (see Figure 25). For building type 2b, 3a and 3b renovation package 7 becomes profitable over a period of 36 years if the investment cost is reduced by more than 24 %.

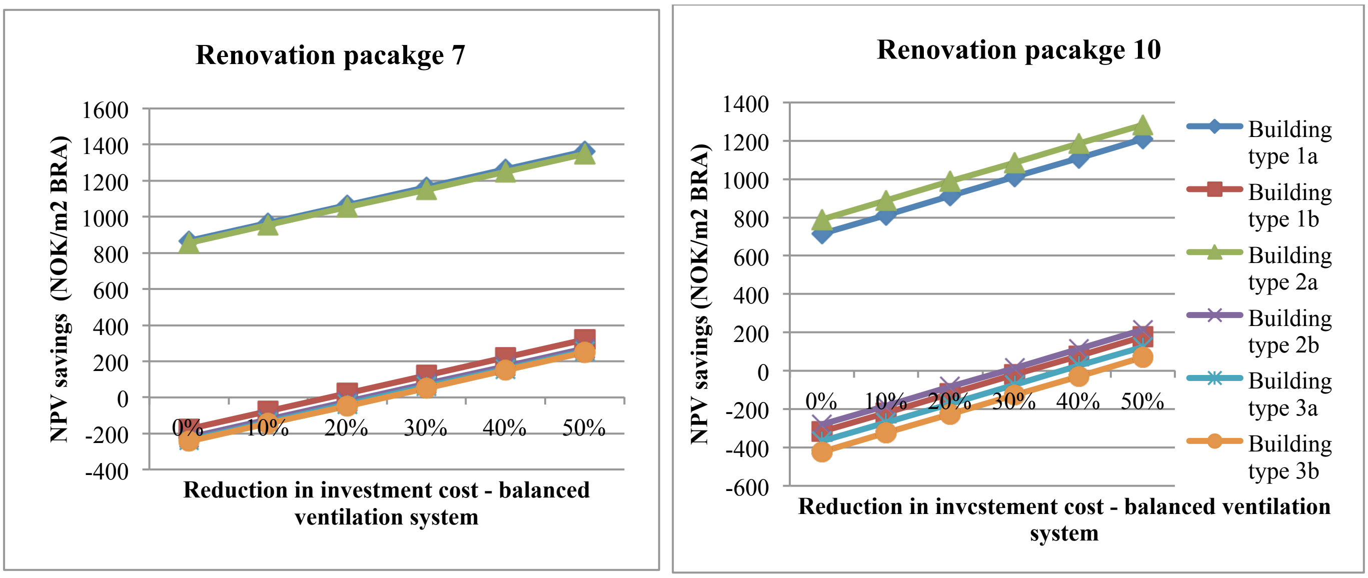


Figure 25: Sensitivity analysis on the investment cost of a balanced ventilation system

Renovation package 10 becomes profitable for building type 1b, 2b, 3a and 3b if the investment cost of installing a balanced ventilation system is reduced with more than 32 %, 28 %, 37 % and 43 % respectively. As shown, this renovation package requires the highest reduction in this cost parameter for the two newest building types. It must though be taking into consideration that these building types have a longer remaining lifetime than the other building types, which means that if the analyze period had been to the end of each of the building's lifetime the results may had been different.

4.3 Future development for the aggregated building stock when it comes to energy use

Building type 1 = Apartment blocks built before 1956
Building type 2 = Apartment blocks built between 1956 and 1970
Building type 3 = Apartment blocks built between 1971 and 1980

At the beginning of 2012 the calculated amount of apartments standing from each of the time periods analyzed are 114 228 for building type 1, 84 148 for building type 2, and 78 162 for building type 3. When comparing this number to the number given by Statistics Norway it is quite similar. But the calculated amount is general somewhat lower than what is estimated by Statistic Norway. The estimated amount from Statistics Norway are 164 554, 106 324 and 90 441 for building type 1, 2 and 3 respectively (Prognosesenteret AS & Entelligens AS, 2012). Using the assumptions that there are 8, 16 and 24 apartments per block in average for building type 1, 2 and 3 respectively (see Table 2), gives a total calculated number of apartment blocks from the segmented building stock model of 14 278, 5 259 and 3 256 for building type 1, 2 and 3 respectively. This means that approximately 5 916 more apartment blocks built before 1956 are calculated to be demolished in the segmented building stock model than what was registered by Statistics Norway (Prognosesenteret AS & Entelligens AS, 2012). However, this error is assumed to be small enough and it is concluded that the model can be used to give a reasonable prognosis of the future development. The development of remaining buildings towards 2050 from the three time periods is given in Figure 26. As the figure show, the energy consumption for these building types decreases whether the energy consumption decrease or not due to the demolition rate.

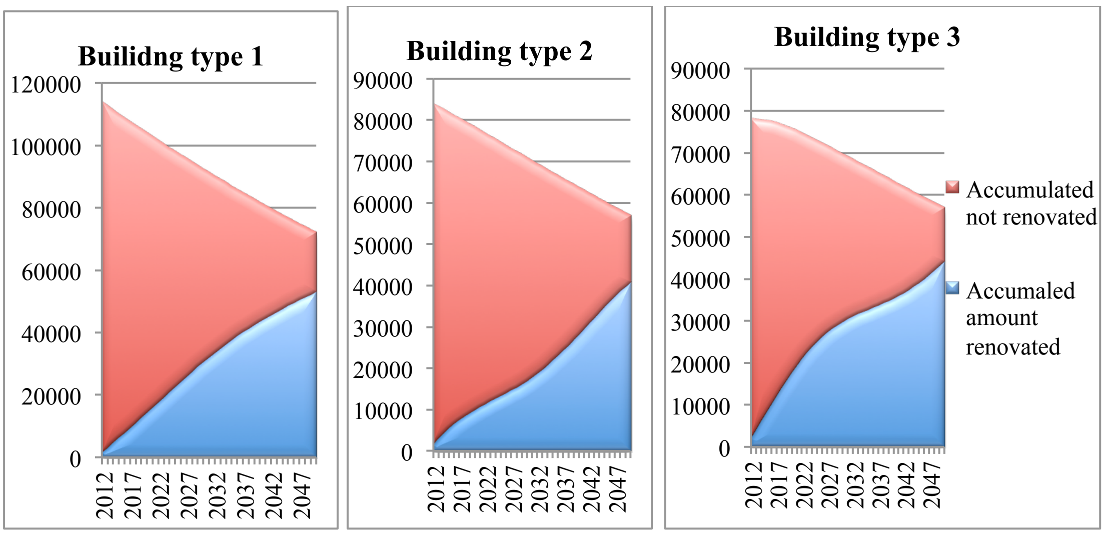


Figure 26: Accumulated amount renovated and not renovated up until 2050

As mentioned in chapter 3.3, a renovation cycle of 40 years is chosen using a normal distribution model to make a good estimation on how the renovation rate develops. For the period between 2012 and 2050 the amount of new renovated buildings increase from year to year and in 2050 approximately 73 %, 70% and 77 % of the buildings built before 1956, between 1956 and 1970, and between 1971 and 1980 respectively have undergone some sort of new renovation. As mentioned earlier, many of the buildings have undergone renovations before 2012, but this is taking into account when calculating the energy use for the different building types before new renovations. Figure 26 shows how the development of renovated and not renovated buildings are assumed to develop up until 2050. Three different future scenarios are analyzed in this thesis; one is a worst case scenario, one is a best case scenario and one is a realistic future scenario.

The calculated energy before and after renovations for the packages seen most suitable are given in Table 41. The energy use before renovation for the different building types is given as an average value between energy use in original state and historical refurbished state using the percentages given in Figure 3 (see chapter 2.4). All the values are given in kWh/m^2 heated floor area per year.

Table 41: Calculated energy use before and after renovation

		Before 1956	1956-1970	1971-1980
Without any upgrades to the building	Electricity use	135.2	129.9	100.6
	Wood use	15.6	9.0	4.7
	Oil use	14.6	13.4	5.9
	District heating use	0.0	0.0	0.0
TEK10 envelope upgrade (2)	Electricity use	82.8	80.8	77.1
	Wood use	7.6	4.4	3.1
	Oil use	7.1	6.6	3.9
	District heating use	0	0	0
Passive house envelope upgrade (3)	Electricity use	63.3	62.5	60.1
	Wood use	4.6	2.7	1.9
	Oil use	4.3	4.0	2.3
	District heating use	0.0	0.0	0.0
TEK10 envelope upgrade + air-to-air heat pump (6)	Electricity use	65.4	63.2	59.5
	Wood use	0.0	0.0	0.0
	Oil use	0.0	0.0	0.0
	District heating use	0.0	0.0	0.0
TEK10 envelope upgrade + connect to district heating (8)	Electricity use	0.0	0.0	0.0
	Wood use	0.0	0.0	0.0
	Oil use	0.0	0.0	0.0
	District heating use	102.2	97.8	90.2
Passive house envelope upgrade + air-to-air heat pump (9)	Electricity use	52.9	51.8	49.5
	Wood use	0.0	0.0	0.0
	Oil use	0.0	0.0	0.0
	District heating use	0.0	0.0	0.0
Passive house envelope upgrade + balanced ventilation system with 80 % heat recovery (10)	Electricity use	39.5	37.3	36.8
	Wood use	0.8	0.3	0.2
	Oil use	0.8	0.5	0.2
	District heating use	0.0	0.0	0.0
Passive house envelope upgrade + installing a solar collector system + balanced ventilation system (14)	Electricity use	17.00	15.90	15.54
	Wood use	0.00	0.00	0.00
	Oil use	0.00	0.00	0.00
	District heating use	0.0	0.0	0.0

4.3.1 Worst case scenario

The worst case scenario includes no energy related upgrades except minor window improvements, which is the same as done in base case (renovation package 0). If nothing else is upgraded the future energy consumption for this part of the Norwegian building stock is supposed to follow a development as given in Figure 27.

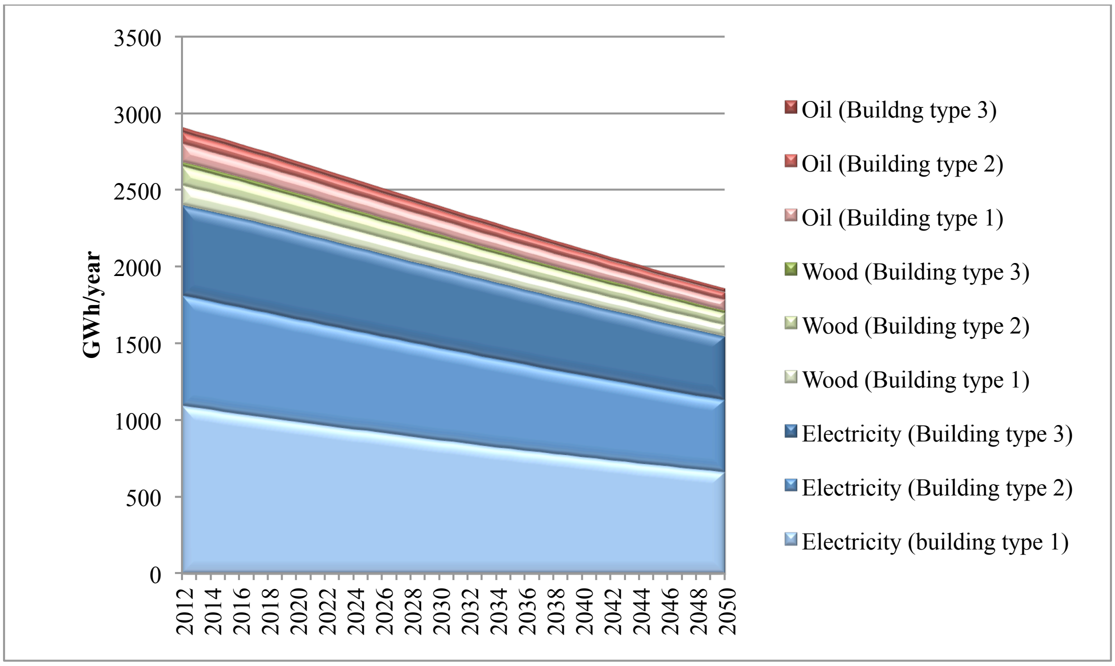


Figure 27: Worst case scenario development towards 2050 for apartment blocks built before 1980

As Figure 27 shows, the energy is reduced some, but mostly because of the demolition rate. Following a future scenario like this do not lead to a huge energy reduction in the apartment blocks still standing in 2050, and compared to the minority these buildings represents of the expected total amount of apartment blocks in 2050 they will stand for a much bigger part of the energy use than what is optimal.

Since only emissions connected to the use-phase is included in the analysis, the yearly greenhouse gas emissions follow the same slope as the energy consumption curve given in Figure 27. The calculated amount of greenhouse gas emissions emitted in 2012 with the energy composition given in this project is calculated to be 1 439 ktonnes/year. In 2050 the yearly emission rate is calculated to have decreased relatively linearly down to 922 ktonnes. This is when a European average emission rate for electricity is used. The reduction in yearly greenhouse gas emissions from 2012 to 2050 is mainly connected to the demolition rate in this scenario development.

Since the greenhouse gas emissions is only connected to the usage of energy, the calculated yearly emissions are very dependent on the GHG-factor for electricity. Table 42 shows how much the calculated yearly emissions in 2012 and 2050 vary when changing from Norwegian electricity mix to Nordic electricity mix to European electricity mix. The emission factors for wood and oil remain constant.

Table 42: Yearly GHG-emissions in 2012 and 2050 for different emission factors for electricity (worst case scenario)

Emission factor[19]	GHG emissions – 2012 (ktonnes CO_2-eq./year)	GHG emissions – 2050 (ktonnes CO_2-eq./year)
Norwegian mix (0.05 kg CO_2-eq./kWh)	257	161
Nordic mix (0.2 kg CO_2-eq./kWh)	617	393
European mix (0.542 kg CO_2-eq./kWh)	1 439	922

As shown in Table 42 the GHG emissions emitted from this part of the Norwegian building stock is very dependent on the emission factor used. If a Norwegian mix is used the total emissions are 1/6 of what it is if a European mix is used. This shows the importance of using an appropriate emission factor. However, it is very difficult to know what the appropriate factor is since it is very dependent on the geographical area that is included in the analysis. For Norwegian conditions it would be correct to use a Norwegian emission factor. However, since emissions travel over borders, it is important to see all land together, and then a European mix would be most suitable. Using a European mix also gives a stronger incentive for reducing the electricity use in Norway. By reducing the electricity use and developing a proper electricity grid between land borders it is possible to use climate neutral electricity from Norway in regions that use less environmental friendly electricity.

19 Source: (CICERO, 2012)

4.3.2 Best case scenario

Looking at a best case scenario where all buildings that undergo a renovation undergo a passive house envelope upgrade, install a balanced ventilation system with 80 % heat recovery, and install solar collectors with electric boilers to cover the peak load, the future development in energy use for apartments built before 1980 will be as shown in Figure 28.

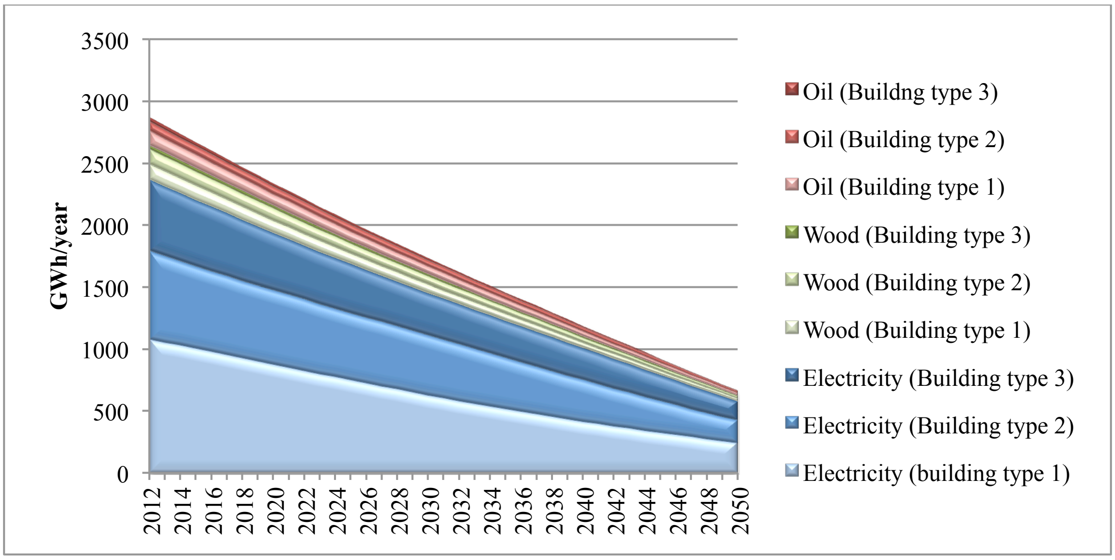


Figure 28: Best case scenario development towards 2050 for apartment blocks built before 1980

This development is though not very likely since this renovation package is very expensive, and gives a negative net present value over a period of 36 years (see chapter 4.2). To be profitable the investment cost of solar collector has to decrease down to 8.5 NOK/kWh (see chapter 4.2.2.4). In buildings that already have a water-based heating system installed this renovation package can become profitable at a higher cost (see chapter 4.2.2.4). Implementing this renovation package as the only refurbishment measure gives an increase in energy savings in 2050 of approximately 1.2 TWh/year compared to the worst case scenario. This amount corresponds to Drammen's annual electricity consumption (Energilink, 2006).

The development of greenhouse gas emissions for this future scenario will follow the same slope as the energy development (see Figure 28). The total emitted CO_2-emissions in 2012 and 2050 for different emission factors for electricity is given in Table 43.

Table 43: Yearly CO_2-emissions in 2012 and 2050 for different emission factors for electricity (best case scenario)

Emission factor[20]	GHG emissions – 2012 (ktonnes CO_2-eq./year)	GHG emissions – 2050 (ktonnes CO_2-eq./year)
Norwegian mix (0.05 kg CO_2-eq./kWh)	253	52
Nordic mix (0.2 kg CO_2-eq./kWh)	608	140
European mix (0.542 kg CO_2-eq./kWh)	1 418	399

Compared to the worst case scenario the CO_2-emissions in 2050 are estimated to be reduced with 56.7%, which is a major improvement and fulfills the goal set by UN Climate Change Convention (Randers, 2006).

[20] Source: (CICERO, 2012)

4.3.3 "Realistic" future scenario

The future prospective that is seen most realistic includes different renovation packages. Some of the buildings that undergo renovation are upgraded to TEK10 level, some to passive house level and some also include extra measures like balanced ventilation system and installation of heat pump or solar collectors. The composition of different renovation packages are chosen based on the results from the NPV calculations given in chapter 4.2. Table 44 shows the composition that is seen most realistic.

Table 44: Composition of different renovations for the realistic future energy development

	Before 1956	1956-1970	1971-1980
TEK10 envelope upgrade (2)	20%	20%	20%
Passive house envelope upgrade (3)	5%	5%	5%
TEK10 envelope upgrade + air-to-air heat pump (6)	20%	20%	20%
TEK10 envelope upgrade + connect to district heating (8)[21]	10%	10%	10%
Passive house envelope upgrade + air-to-air heat pump (9)	10%	10%	10%
Passive house envelope upgrade + balanced ventilation system with 80 % heat recovery (10)	25%	25%	30%
Passive house envelope upgrade + installing a solar collector system + balanced ventilation system (14)[22]	10%	10%	5%

Renovation package 14 is only seen realistic if there is installed a water-based heating system in the building originally. But since approximately 40 %, 29 % and 19 % of the apartments built before 1956, between 1956-1970, and between 1971-1980 respectively are assumed built with a water-based heating system, it is realistic to anticipate that 5-10% of the buildings renovated use renovation package 14 (Pettersen , Lars, Wigenstad, & Dokka, 2005). As shown in Table 44 it is anticipated that 25-30 % are upgraded to passive house standard with a balanced ventilation system installed even though this renovation package don't give positive NPV values for all the building types (see Figure 17 in chapter 4.2). This is because it is necessary to install a balanced ventilation system in passive houses to ensure a good indoor quality (Holøs, Maltha, & Berge, 2013). It is also anticipated that there is a high willingness to pay for comfort. Some buildings (15 %) are though assumed upgraded to passive house level without installing a balanced ventilation system due to the high investment cost connected to installation of a balanced ventilation system. This is assumed to be somewhat realistic, as it is difficult to achieve a complete passive house level when upgrading old buildings. It is therefore anticipated that the air quality when using a natural ventilation system will be satisfying for some buildings after a passive house upgrade.

Since passive house standard is difficult to achieve for buildings without installation of either a balanced ventilation system with heat recovery, as it requires a heating demand to space heating lower than 15 kWh/m^2year (NS3700, 2013), it is anticipated that many of the buildings that undergo refurbishment are only upgraded to TEK10 level. A building with a

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[21] Realistic for buildings that already have a water-based heating system installed

TEK10 approved envelope do not require a balanced ventilation system to get satisfying air quality since the building envelope is not as tight as for passive house buildings (Holøs, Maltha, & Berge, 2013).

Assuming a combination of refurbishment packages as given in Table 44 a future energy development like given in Figure 29 can be assumed.

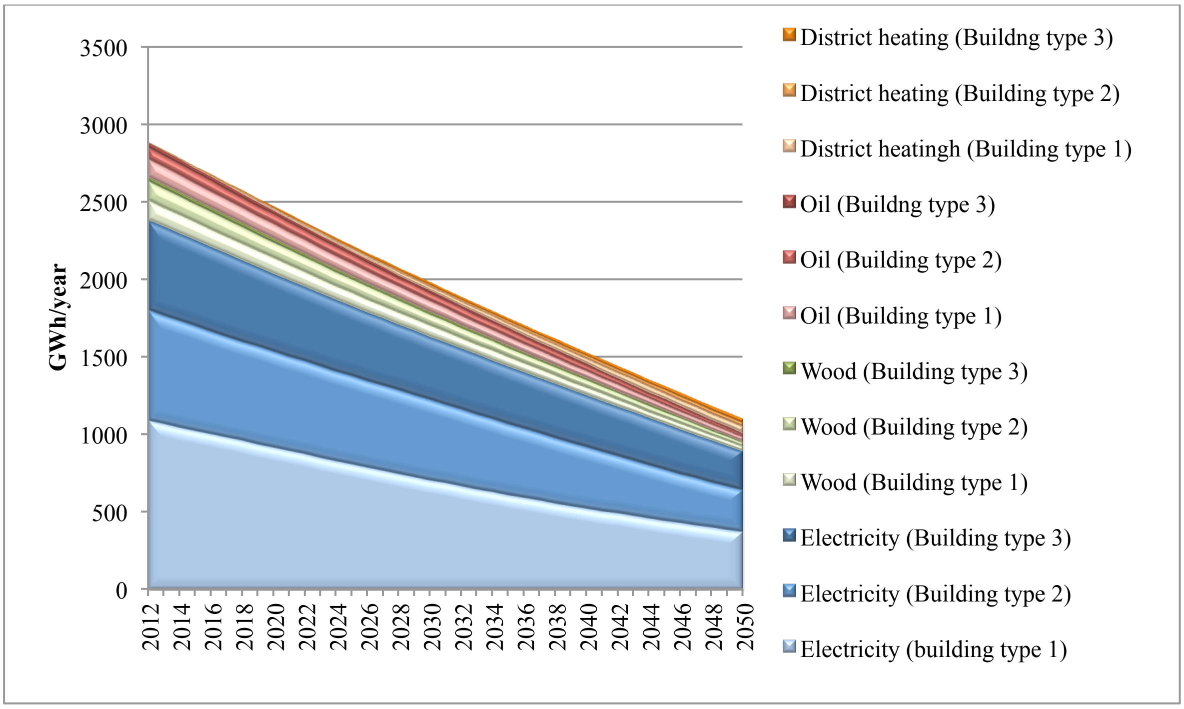

Figure 29: "Realistic" future energy development towards 2050 for apartment blocks built before 1980

Compared to the worst case scenario following a reduction pattern as given in this section leads to an energy reduction in 2050 of 0.76 TWh. This is 37 % lower than the best possible reduction possibility analyzed in this study (see Figure 28 for the best case scenario), but a reduction like this is seen very realistic, and compared to the worst case scenario the savings are still good.

The development of greenhouse gas emissions for this future scenario follows the same slope as the energy development in Figure 29. The total emitted CO_2-emissions in 2012 and 2050 for different emission factors for electricity are given in Table 45.

Table 45: Yearly CO_2-emissions in 2012 and 2050 for different emission factors for electricity ("realistic" futur scenario)

Emission factor[22]	GHG emissions – 2012 (ktonnes CO_2-eq./year)	GHG emissions – 2050 (ktonnes CO_2-eq./year)
Norwegian mix (0.05 kg CO_2-eq./kWh)	254	72
Nordic mix (0.2 kg CO_2-eq./kWh)	611	193
European mix (0.542 kg CO_2-eq./kWh)	1 425	469

Compared to the worst case scenario the CO_2-emissions in 2050 are estimated to be reduced with 39 %, which is a moderate reduction.

[22] Source: (CICERO, 2012)

5 Recommendations and conclusions

Amount of extra isolation required to upgrade the building envelope to TEK10 or passive house standard varies depending on the quality of the buildings in original state. Generally the quality of the buildings decreases with the age of the buildings as the building regulations have become stricter during the years. A typical building constructed before 1956 needs 200 mm extra mineral wool in walls, and 200 mm extra mineral wool in roof and floors that are connected to an unheated attic or basement to accomplish U-values that satisfy TEK10 (see chapter 3.2.1). This is seen as achievable and is therefore recommended as it gives a total energy reduction of 136 kWh/m^{2}year if the building is in original state. If the building is in historical refurbished state it is necessary with 150 mm extra mineral wool in external walls and 100 mm extra mineral wool in roof and floors. The total annual energy reduction from this state to TEK10 state is 54.6 kWh/m^2. Similar energy savings can be seen for apartments built during the period 1956-1970. For apartments built between 1970 and 1980 the quality of the building in original state is considerably better, which implies that upgrading these buildings to a TEK10-level requires less extra insulation thickness. The energy saving potential for upgrading an apartment block in original state from this period to TEK10 level is estimated to be 40.1 kWh/m^{2}year.

Based on the life cycle costing analysis performed for the different renovation packages included in this report it is concluded that it is efficient over a period of 36 years to upgrade all of the building types to TEK10 level and passive house level as well as implementing air-to-air heat pumps as supplementary measures to reduce the energy need further. However, this is when a balanced ventilation system is not included in the renovation package. For passive houses it is generally recommended to install a balanced ventilation system, as the indoor air quality can be unsatisfactory when only using a natural ventilation system. The LCC analysis shows that the investment cost connected to installation of a balanced ventilation system general is too high to make it an efficient solution for all building types. However, upgrading the building envelope to either TEK10 level or passive house level combined with installation of a balanced ventilation system with heat recovery is calculated to be efficient for the two oldest building types in original state.

Installation of a water-based heating system together with installation of either air-to-water heat pumps or solar collectors is calculated to have a negative net present value compared to base case, and are therefore not seen efficient. However, this is mainly because of high installation costs, because the energy saving potential is highest for these renovation packages. For the future scenario development for the part of the Norwegian building stock analyzed in this project it is concluded that if all renovations are of type 14 (passive house envelope upgrade, installation of solar collectors and installation of a balanced ventilation system) the total energy saving potential in 2050 compared to the worst case scenario is approximately 1.2 TWh/year. This amount corresponds to Drammen's annual electricity consumption (Energilink, 2006). This scenario is seen as the best possible development, but is seen somewhat unrealistic due to high investment and maintenance costs connected to the energy efficiency measures. A more realistic future scenario is seen as a combination of the most profitable solutions, such as TEK10 envelope upgrade and passive house upgrade where some of the buildings are supplemented with extra efficiency measures such as heat pumps, balanced ventilation systems or solar collectors. It is anticipated that some of the building types already have a water-based heating system installed before renovation, which makes the renovation packages that includes a water-based heating system more efficient and realistic. The realistic saving potential in 2050 is estimated to be 0.76 TWh/year. This is when a combination of several profitable renovation packages is implemented to the part of the Norwegian dwelling stock analyzed in this study.

Following a best case scenario of future development also leads to a major reduction in greenhouse gas emissions. It is estimated that by upgrading approximately 70 % of the apartment blocks standing in 2050 to the best possible quality it is possible to reduce the greenhouse gas emissions with 56.7 %. Choosing a more realistic but still optimistic future development gives a 39 % reduction in greenhouse gas emissions by the year 2050. These results show that there are major benefits in terms of energy savings, greenhouse gas emission reduction and financial savings by upgrading existing buildings.

6 Further work

In this Master Thesis only a simple carbon emission analysis that include emissions connected to the usage phase is completed. In further studies it can be interesting to perform a complete life cycle analysis of each renovation package to see if there are major emissions connected to production and transportation of materials etc. that is necessary for the energy efficiency measure.

It can also be interesting to perform a more detailed analysis of a specific building from each of the given periods and perform a more detailed life cycle costing that includes costs connected to demolition and reconstruction since the economical output of the study may change when including these parameters.

Three different predictions of the future energy situation for the part of the Norwegian dwelling stock analyzed in this report is made in this master thesis. In further works it can be interesting to look at other future predictions, and maybe change the renovation intervals, so that less or more buildings undergo renovations.

Since the energy demand is very dependent on user behavior, the impact of this element should be included in further work. Energy efficiency measures connected to lighting and cooling should also be included since energy saving lamps and control systems for lighting may play an important role in further energy savings in good insulated buildings.

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Appendix A – Required insulation thickness

Calculation of insulation thickness after TEK10- and passive house refurbishments

Mineral wool, $\lambda = 0.037\ W/mK$

Before 1956						
	Original state		TEK10		Passive house	
	U-value	Mineral wool thickness	U-value	Extra insulation thickness	U-value	Extra insulation thickness
External walls	0.82	0	0.18	160	0.12	263
Roof	0.81	0	0.15	201	0.09	365
Floor	0.55	0	0.15	179	0.08	395

Before 1956						
	Historical refurbished state		TEK10		Passive house	
	U-value	Mineral wool thickness	U-value	Extra insulation thickness	U-value	Extra insulation thickness
External walls	0.41	50	0.18	115	0.12	218
Roof	0.31	100	0.15	127	0.09	292
Floor	0.26	100	0.15	104	0.08	320

1956-1970						
	Original state		TEK10		Passive house	
	U-value	Mineral wool thickness	U-value	Extra insulation thickness	U-value	Extra insulation thickness
External walls	0.96	0	0.18	167	0.12	270
Roof	0.33	100	0.15	135	0.09	299
Floor	0.38	50	0.15	149	0.08	365

1956-1970						
	Historical refurbished state		TEK10		Passive house	
	U-value	Mineral wool thickness	U-value	Extra insulation thickness	U-value	Extra insulation thickness
External walls	0.29	100	0.18	78	0.12	181
Roof	0.24	150	0.15	93	0.09	257
Floor	0.18	100	0.15	41	0.08	257

1971-1980						
	Original state		TEK10		Passive house	
	U-value	Mineral wool thickness	U-value	Extra insulation thickness	U-value	Extra insulation thickness
External walls	0.34	100	0.18	97	0.12	200
Roof	0.21	180	0.15	70	0.09	235
Floor	0.24	50	0.15	93	0.08	308

1971-1980						
	Historical refurbished state		TEK10		Passive house	
	U-value	Mineral wool thickness	U-value	Extra insulation thickness	U-value	Extra insulation thickness
External walls	0.18	200	0.18	0	0.12	103
Roof	0.21	250	0.15	70	0.09	235
Floor	0.14	100	0.15	0	0.08	198

Insulation thickness between 200-250 gives a choice of isolation thickness of 250 mm.
Insulation thickness between 200-250 gives a choice of isolation thickness of 250 mm.
Insulation thickness between 250-300 gives a choice of isolation thickness of 300 mm.
Insulation thickness between 300-350 gives a choice of isolation thickness of 350 mm.
Insulation thickness between 350-400 gives a choice of isolation thickness of 400 mm.

Appendix B – Overview of the different renovation packages included in this report

Renovation package	Explanation
0	No energy-related upgrades except improving the U-values of the windows to 1.4 W/m^2K
1	Upgrading windows to passive house level
2	TEK10 envelope upgrade
3	Passive house envelope upgrade
4	Installation of air-to-air heat pump only
5	Installation of balanced ventilation system with 70 % heat recovery
6	TEK10 envelope upgrade + installation of air-to-air heat pump
7	TEK10 envelope upgrade + installation of balanced ventilation system with 70 % heat recovery
8	TEK10 envelope upgrade + Installation of water-based heating system with radiators + connecting to district heating
9	Passive house envelope upgrade + installation of air-to-air heat pump
10	Passive house envelope upgrade +installation of balanced ventilation system with 80 % heat recovery
11	Passive house envelope upgrade + Installation of water-based heating system with radiators + connecting to district heating
12	Passive house envelope upgrade + Installation of water-based heating system + installation of solar collectors
13	Passive house envelope upgrade +Installation of water-based heating system with radiators + installation of air-to-water heat pumps
14	Passive house envelope upgrade + Installation of water-based heating system + installation of solar collectors + installation of balanced ventilation system with heat recovery

Appendix C – Cost information

All costs includes 25 % VAT.

Energy prices

Energy source	Price	Unit	Source
Electricity	0.893	NOK/kWh	(SSB, 2014)
District heating	0.8037	NOK/kWh	90% of the electricity price
Heat from solar collectors	0	NOK/kWh	Produced on site
Wood	0.625	NOK/kWh	(Hofstad, 2007)

Investment costs for energy efficiency measures related to the heating system

Installation type	Cost	Unit	Source
Air-to-air heat pump, capacity 3 kW	25 402	NOK/unit	(Jensen & Rudén, 2013)
Air-to-air heat pump, capacity 3 kW	32 921	NOK/unit	(Jensen & Rudén, 2013)
Air-to-water heat pump, capacity 3 kW	89 000	NOK/unit	(TOSHIBA, 2014)
District heating, customer central, capacity 50 kW	115 500	NOK/unit	(Rosenberg, 2010)
District heating, customer central, capacity 100 kW	131 250	NOK/unit	(Rosenberg, 2010)
District heating, customer central, capacity 150 kW	141 750	NOK/unit	(Rosenberg, 2010)
Water heaters, direct electricity	6 400	NOK/unit	(Braathen, 2013)
Water heaters, solar collectors	13 750	NOK/unit	(Braathen, 2013)
Water heaters, district heating	11 250	NOK/unit	(Braathen, 2013)
Water heaters, heat pumps	15 000	NOK/unit	(Braathen, 2013)
Electric boiler	925	NOK/kW	(Hofstad, 2007)
Balanced ventilation system, apartment block	790	NOK/m^2 BRA	(Jensen & Rudén, 2013)
Solar collectors on roof –yearly production at 50 °C = 3 274 kWh	88 974	NOK/unit	(Jensen & Rudén, 2013)
Solar collectors on roof –yearly production at 50 °C = 6 548 kWh	164 730	NOK/unit	(Jensen & Rudén, 2013)
Panel heaters, direct electricity	158	NOK/m^2 BRA	(Holte AS, 2014)
Waterborne heating system - radiators	810.5	NOK/m^2 BRA	(Jensen & Rudén, 2013)

Investment costs for efficiency measures related to the building envelope

Windows and doors

Type	Cost	Unit	Source
Windows/door, U-value =1.4 W/m^2K	3 195	NOK/m^2 window	(Tindevindu, 2014)
Windows/door, U-value =1.4 W/m^2K	3 305	NOK/m^2 window	(Tindevindu, 2014)
Windows/door, U-value =1.4 W/m^2K	5 076	NOK/m^2 window	(Jensen & Rudén, 2013)

Exterior walls

Material costs

Insulation thickness	**Cost**	**Unit**	**Source**
50 mm	52.9	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
75 mm	74.4	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
100 mm	104.5	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
125 mm	124.9	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
150 mm	156.4	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
200 mm	211.2	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
250 mm	291.7	NOK/m^2 insulated surface	(ROCKWOOL, 2014)

Transportation costs

Insulation thickness	**Cost**	**Unit**	**Source**
50 mm	1.0	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
70 mm	1.4	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
100 mm	1.88	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
123 mm	2.78	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
150 mm	2.78	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
170/200 mm	3.54	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
250 mm	3.73	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
300 mm	7.67	NOK/m^2 insulated surface	(ROCKWOOL, 2014)

Labor costs

Insulation thickness	**Cost**	**Unit**	**Source**
50 mm	88	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
100 mm	119	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
150 mm	119	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
200 mm	119	NOK/m^2 insulated surface	(Førland-Larsen, 2012)

Total investment cost for the different building types (per heated floor area (BRA)) to TEK10-standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
100 mm	-	-	-	152	58.3	-
150 mm	-	215	-	-	-	-
200 mm	258	-	225	-	-	-

Total investment cost for the different building types (per heated floor area (BRA)) to passive house standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
100 mm	-	-	-	-		97.5
150 mm	-	-	-	-	122.5	-
200 mm	-	-	-	240	-	-
250 mm	-	320	-	-	-	-
300 mm	364	-	318	-	-	-

Roof

Material costs

Insulation thickness	Cost	Unit	Source
50 mm	19.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
70 mm	27	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
98 mm	37.5	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
123 mm	47	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
148 mm	55.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
170 mm	60.1	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
200 mm	86.6	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
250 mm	105.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
300 mm	128.2	NOK/m^2 insulated surface	(ROCKWOOL, 2014)

Costs due to transportation are the same as for exterior walls

Labor costs

Insulation thickness	Cost	Unit	Source
50 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
100 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
150 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
200 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)

Total investment cost for the different building types (per heated floor area (BRA)) to TEK10-standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
70 mm	-	-	-	-	20.1	-
100 mm	-	-	-	22.9	-	-
150 mm	-	27.6	28	-	-	-
250 mm	40.1	-	-	-	-	-

Total investment cost for the different building types (per heated floor area (BRA)) to passive house standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
150 mm	-	-	-	-	-	27.6
220 mm	-	-	-	-	35.5	-
250 mm	-	-	-	40.2	-	-
300 mm	-	47	47	-	-	-
400 mm	56.8	-	-	-	-	-

Roof

Material costs

Insulation thickness	Cost	Unit	Source
50 mm	19.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
70 mm	27	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
98 mm	37.5	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
123 mm	47	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
148 mm	55.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
170 mm	60.1	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
200 mm	86.6	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
250 mm	105.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
300 mm	128.2	NOK/m^2 insulated surface	(ROCKWOOL, 2014)

Costs due to transportation are the same as for exterior walls

Labor costs

Insulation thickness	Cost	Unit	Source
50 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
100 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
150 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)
200 mm	52	NOK/m^2 insulated surface	(Førland-Larsen, 2012)

Total investment cost for the different building types (per heated floor area (BRA)) to TEK10-standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
70 mm	-	-	-	-	20.1	-
100 mm	-	-	-	22.9	-	-
150 mm	-	27.6	28	-	-	-
250 mm	40.1	-	-	-	-	-

Total investment cost for the different building types (per heated floor area (BRA)) to passive house standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
150 mm	-	-	-	-	-	27.6
220 mm	-	-	-	-	35.5	-
250 mm	-	-	-	40.2	-	-
300 mm	-	47	47	-	-	-
400 mm	56.8	-	-	-	-	-

Floor

Material costs

Insulation thickness	Cost	Unit	Source
50 mm	19.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
70 mm	27	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
98 mm	37.5	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
123 mm	47	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
148 mm	55.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
170 mm	60.1	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
200 mm	86.6	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
250 mm	105.8	NOK/m^2 insulated surface	(ROCKWOOL, 2014)
300 mm	128.2	NOK/m^2 insulated surface	(ROCKWOOL, 2014)

Costs due to transportation and labor are the same as for exterior walls

Total investment cost for the different building types (per heated floor area (BRA)) to TEK10-standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
50 mm	-	-	-	-	-	18-2
100 mm	-	22.8	-	22.9	22.9	-
150 mm	-	-	27.6	-	-	-
200 mm	36	-	-	-	-	-

Total investment cost for the different building types (per heated floor area (BRA)) to passive house standard

Required extra insulation thickness	Before 1956		Between 1956-1970		Between 1971-1980	
	Original state	Historical refurbished state	Original state	Historical refurbished state	Original state	Historical refurbished state
250 mm	-	-	-	-	-	40.4
300 mm	-	47	-	47	47	-
350 mm	-	-	52.2	-	-	-
400 mm	56.8	-	-	-	-	-

Appendix D – Calculation models

The energy balance model, LCC-model and the Scenario-model are excel-models made by the author and are attached as a electronic appendix.

The energy balance model is called Appendix D1, the LCC model is called Appendix D2, while the Scenario model is called Appendix D3

Appendix E – Lifetime

Balanced ventilation system

From Holte FDV-nøkkelen 2014 (Holte AS, 2014) there are given lifetime intervals on several components in a balanced ventilation system, but not an average value on the entire system. Since the cost parameter used is for the total installation cost an average value for the lifetime of the system has to be estimated.

Balanced ventilation system	Short	Normal	Long	Average
Heating coil	15	20	25	20
Filter	10	15	20	15
Supply air fan	20	40	50	35
Exhaust fan	10	20	30	20
Humidifier unit	5	10	20	12
Automatic commissioning	10	15	20	15
Channels	20	25	35	27
Damper	20	30	40	30
Safety valves	15	40	50	35
Roof hood	10	25	30	20
Heat recovery unit	15	20	25	20
Average lifetime for entire system				**23**

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