

EPT-M-2014-112

MASTER THESIS

for

Student Ragni Kristin Storvolleng

Spring 2014

**Dynamics of energy and carbon emissions in residential building stocks –
The role of solutions for single-family houses***Endringer i boligmassens energiforbruk og karbonutslipp –
Betydningen av løsninger for enfamiliehus***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 single-family houses, including scenarios for refurbishment strategies, energy generation and occupancy behaviour. Additionally, the student shall examine the influence of life cycle costs of energy measures.

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.

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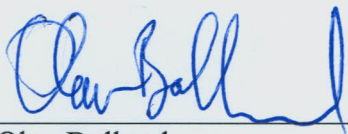
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- ☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14th January 2014



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Preface

This MSc Thesis has been carried out during the spring of 2014, at the Department of Energy and Process Engineering (EPT), at the Norwegian University of Science and Technology. The thesis is a continuation of the work carried out in the MSc Project (Storvolleng, 2013), during the fall of 2013, and is credited 30 points.

The Academic Supervisor has been Helge Brattebø at the Department of Energy and Process Engineering. In addition an economic assessment has been carried out in collaboration with Hjellnes Consult, where Guillermo Duran Moro has been the primary supervisor. Further, Reyn O’Born has been co-supervisor during this work.

The thesis focuses on the energy situation of Norwegian single-family dwellings constructed before 1980. It consists of a three part analysis assessing the energy demand and rehabilitation strategies, the economics and future scenarios, concerning this particular part of the dwelling stock.

During this work many people have been of great assistance. I would like to sincerely thank my supervisor Helge Brattebø for invaluable guidance during the work carried out, both this spring and during last fall. Furthermore I would like to thank Reyn O’Born for information on Primary Energy Factors and for always keeping an open door. I would also like to thank Nina Sandberg for explaining the Segmented Building Stock model, used for the scenario analysis carried out in the last part of this work.

Furthermore Hjellnes Consult AS deserves my appreciation. Especially Guillermo Duran Moro which provided insight to Life Cycle Costing (LCC), but also the rest of the office for letting me visit, and answering all of my questions.

Finally I would like to thank my three fellow students, Martha Baltrusiewicz, Marie Folstad and Anja Myreng Skaran. During the early weeks of last fall we all established Energy Balance Models, and decided together to continue the work based on Marie’s model. The combined effort seems to have yielded good results and I’m grateful for their contributions and our successful collaboration. In addition Anja visited Hjellnes first, and brought back much information on LCC which made the economic assessment a lot easier. Furthermore their insights and readiness to discuss every little problem or uncertainty have been of great value to me. Cooperation with friends also has the added benefit of making even gathering information on costs a good time.

Ragni Kristin Trolie Storvolleng

Trondheim, June 13, 2014

Abstract

With an ever increasing global energy consumption associated with Green House Gas (GHG) emissions, energy efficiency is becoming an important concept in most developed countries. In order to meet the future demand, while simultaneously reduce the fossil fuel consumption, both the renewable energy production and energy efficiency need to be increased. Consequentially, a strong focus is placed on energy efficiency within all sectors. Amongst these legislative acts are imposed on the building sector.

The objective of the current MSc Thesis is to contribute to the understanding of the long-term dynamics of energy and carbon emissions in the residential building stock. This work is only concerned with single-family dwellings originating from before 1980, with other theses focusing on the rest of the dwelling stock.

A three part analysis has been carried out assessing the energy demand, economics and future possible scenarios in the Norwegian dwelling stock. The first part established and examined the energy balance of current dwellings, as well as how it changes due to rehabilitation. An economic analysis was carried out in the second part considering the economics of implementing the rehabilitation measures. Based on the outcome of the economic assessment, some rehabilitation measures were further used in a scenario analysis, providing possible projections of future energy demand and associated emissions, as a result of these rehabilitation measures being implemented.

According to the results, rehabilitation of old single-family dwellings managed the TEK 10 standard and further approached Passive House level as long as balanced ventilation was installed. Nevertheless, due to the constructional thermal bridge surcharge factor, which was held constant, Passive House level, was not entirely reached.

According to the economic analysis balanced ventilation was profitable with full Passive House rehabilitation, while not with TEK 10 rehabilitation, where the energy savings were not great enough to counterbalance this additional investment. Furthermore, air-to-air heat pumps were profitable for all cases. On the other hand air-to-water heat pumps were not, as these require installment of a waterborne space heating system, which is very expensive. Additionally the electricity price was found to be very influential. For instance, the Base Case Net Present Value (NPV) increased by 37% if the electricity price was doubled throughout the period, and all rehabilitation packages, but one, will become profitable.

If zero-energy level was imposed on all rehabilitated buildings the accumulated energy savings would increase with 28% compared to the Base Case situation. However, this is not a very likely scenario, and savings indicated by less ambitious scenarios are 12 – 19%, with accumulated emission saving of up to 7 Mton CO₂-eq. Emissions resulting from the building stock was remarkable high compared to other studies, and is due to emission intensities being attributed to both the electricity mix and biomass combustion. The electricity mix was found to have major influence on the emissions resulting from the building sector. Hence, rehabilitation measures lowering the electricity demand will induce the largest emission savings. Furthermore, a preliminary analysis of primary energy showed that taking this into account will increase the energy consumption significantly and the electricity mix chosen will greatly influence the results.

Sammendrag

Verdens økende energibehov og utslipp av drivhusgasser har ført til at energieffektivitet har blitt et viktig konsept i de fleste i-land. For å kunne møte morgendagens energibehov samtidig som forbruket av fossil energi reduseres, kreves både økt produksjon fra fornybare kilder og mer effektiv bruk av energien. I dag stilles derfor strenge krav til energieffektivitet innen alle sektorer, og politiske virkemidler settes også inn overfor bygningssektoren.

Formålet med masteroppgaven er å bidra til forståelsen for dynamikken som på lang sikt påvirker energiforbruket i, og utslippene av drivhusgasser fra den norske boligmassen. Arbeidet fokuserer kun på eldre eneboliger som er konstruert før 1980, da andre masteroppgaver tar for seg resten av boligmassen.

Arbeidet er utført som en tredelt analyse som tar for seg energibehov, økonomien og framtidige scenarioer i den norske boligmassen. Energibalansen til dagens bygninger i tillegg til endringene som følge av rehabiliteringer ble først kalkulert. Videre ble det økonomiske aspektet ved disse rehabiliteringene analysert. Basert på resultatet av denne analysen ble noen av rehabiliteringene benyttet i en scenario analyse. Denne analysen viste mulige forløp for energi og utslipp i boligsektoren, som et resultat av de forskjellige rehabiliteringene.

Resultatene viste at rehabilitering av eldre eneboliger kan nå energikravet i TEK 10 og videre nærme seg kravet for Passivhus gitt at balansert ventilasjon installeres. Passivhuskravet ble imidlertid ikke helt oppnådd, fordi verdien for termiske kuldebroer ble holdt konstant gjennom analysen. Derfor ble det utført en sensitivitetsanalyse for denne parameteren som viste at den har stor innvirkning på resultatene.

I følge den økonomiske analysen vil balansert ventilasjon være lønnsomt kombinert med full Passivhusoppgradering, men ikke for TEK 10 rehabilitering. Dette kommer av at energibesparelsen ikke er stor nok til å motvirke den økte investeringen for balansert ventilasjon. Videre er luft-til-luft varmepumper lønnsomme, mens luft-til-vann varmepumper ikke er det på grunn av den høye kostnaden ved å installere vannbårent system. I tillegg påvirker elektrisitetsprisen resultatene i stor grad. For eksempel vil nettonåverdi (NNV) for basisscenarioet øke med 37% hvis elektrisitetsprisen doubles og alle rehabiliteringspakken, bortsett fra en, vil bli lønnsomme.

Hvis alle rehabiliterte bygg oppgraderes til nesten nullenergibygninger vil periodens samlede energibesparelse utgjøre 28% sammenlignet med basisscenarioet. Imidlertid er ikke dette et veldig reelt scenario, og mer reelle potensialer basert på de andre scenarioene tilsvarer 12 – 19% energibesparelse, med samlet utslippsbesparelse opp mot 7 Mton CO₂-ekvivalenter. Utslippene knyttet til bygningsmassen slik de er kalkulert for denne oppgaven er svært høye sammenlignet med litteraturen. Dette kommer av at denne studien forutsetter utslippsintensiteter for både norsk elektrisitetsmiks og forbrenning av biomasse, hvor andre stort sett ikke tar hensyn til disse. I tillegg viser resultatene at utslippsreduksjonen er svært avhengig av elektrisitetsforbruket og elektrisitetsmiksen. Dermed vil tiltak som i stor grad reduserer elektrisitetsforbruket gi store utslippsbesparelser. Videre viste en foreløpig analyse av primærenergi at hvis denne tas hensyn til, vil energiforbruket økes kraftig. I tillegg påvirkes resultatet sterkt av elektrisitetsmiksen som legges til grunn.

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List of Abbreviations

BPIE	Buildings Performance Institute Europe
BTA	Gross Floor Area
BRA	Useful Floor Area
DHW	Domestic Hot Water
EEA	European Energy Agency
EPISCOPE	Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks
EPBD	Energy Performance of Buildings Directive
EU	European Union
IEA	International Energy Agency
IEE	Intelligent Energy Europe
IPCC	Intergovernmental Panel on Climate Change
GHG	Green House Gas
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
MFA	Material Flow Analysis
NPV	Net Present Value
nZEB	nearly Zero Energy Building
RES	Renewable Energy Sources
SSB	Statistics Norway
TABULA	Typology Approach for Building Stock Energy Assessment
TEK	Technical regulations for Norwegian buildings
UFA	Useful Floor Area
ZEB	Zero Energy/Emission Building

1 Introduction

1.1 Objectives and motivation

The ever increasing global energy consumption associated with increasing Green House Gas (GHG) emissions have long been known to cause global problems. Almost three decades have passed since the Brundtland report “Our Common Future” placed environmental awareness on the political agenda (Brundtland and Khalid, 1987). The Intergovernmental Panel on Climate Change (IPCC), established in 1988, has since assessed the environmental impact of human development (IPCC, 2013). Their last Summary for Policymakers underlined the understanding that human influence has been the dominant cause of the observed warming since the mid-20th century (Stocker et al., 2013). In order to substantially limit climate change sustained reductions of GHG emissions are needed. With an ever increasing global energy demand, reducing GHG emissions is not an easy task. Meeting the increased energy demand, especially from the third world without using more fossil fuels cause large challenges. In addition to more renewable energy production energy efficiency become of crucial importance if these challenges are to be overcome. Hence, energy efficiency has become an increasingly important term on the political agenda and is being implemented within all sectors.

The European Union has committed to reduce its emissions to 20% below 1990 levels within 2020, and the leaders have now endorsed the objectives of further reducing the emissions by 80 – 90% compared to 1990 levels by 2050 (European Commission, 2014). Similarly Norway has set reduction targets of 30% reduction compared to 1990 level by 2020 in addition to being carbon neutral by 2050 (Regjeringen.no, 2012).

Both IPCC and IEA have established that energy efficiency is the measure giving largest and fastest reduction of GHGs (DOKKA et al., 2009). Buildings account for a large share of the energy consumption in all countries, and compared to other sectors energy measures are found to be more profitable (DOKKA et al., 2009).

As part of the long term plans both EU and Norway have established energy reduction targets for the building sector. For instance the Energy performance of Buildings Directive (EPBD) sets targets for nearly Zero Energy Buildings both for new constructions and rehabilitation

projects towards 2020 (European Parliament, 2010). The Norwegian building code is stipulated to require Passive House standard on new constructions from 2015 and nearly Zero Energy Buildings from 2020.

Large reduction potentials have been estimated for the Norwegian building stock, varying from 5 – 10 TWh within 2020 and 15 – 40 TWh within 2040, compared to the current level (Rambøll AS and Xrgia AS, 2011) and (Arnstad et al., 2010). However, the models used for these calculations often assume fixed rates for demolition and renovations based on historical data, resulting in less robust numbers. In addition 50% of the existing building stock is privately owned. Hence, there are many decision makers to be convinced if the full potential is to be realized.

The European project EPISCOPE (Energy Performance Indicator Tracking Schemes for Continuous Optimization of refurbishment Processes in European Housing Stocks) is currently examining energy refurbishment processes in the European housing sector, with the objective of making these processes more transparent and effective. The work is a continuation of the project TABULA (Typology Approach for Building Stock Assessment), which established a common methodology for assessing the energy demand in buildings. The EPISCOPE project will carry on until March 2016 and 19 countries are participating. In Norway the Norwegian University of Science and Technology is contributing in this project.

1.2 Research questions

In the current thesis the Norwegian dwelling stock will be further examined in a three part analysis. The work is only concerned with older single-family dwellings as the rest of the dwelling stock is considered in other theses. The thesis will consist of three analyses, an energy balance model, an economic analysis and a scenario analysis. This section presents the objective and research questions defined for each part of the thesis.

The energy balance model will be based on the MSc Project work carried out during the fall of 2013. An energy balance based on the buildings thermal condition, taking into account its energy supply system, along with other parameters is established based on a European methodology (TABULA) (Loga and Diefenbach, 2013) Renovation packages are established based on the principles from the Kyoto Pyramid, aiming to reduce the buildings energy demand. Based on these assumptions the first research question is established.

Research question 1:

How does a buildings energy balance change when applying different rehabilitation strategies and is it possible to rehabilitate old single-family dwellings to Passive House buildings or even nearly Zero Energy Buildings?

Considering that such a large part of the building stock is privately owned an economic analysis of the rehabilitation packages will be carried out based on the principles of Life Cycle Costing (LCC). The objective is to provide information on which rehabilitations are likely to be implemented when considering the costs, and the second research question is defined below.

Research question 2:

How is the economics of rehabilitations likely to affect which rehabilitations that will be carried out during the next decades?

In the last part a scenario analysis will be carried out considering the energy and emission savings if some of the rehabilitation packages are implemented on all rehabilitated buildings. The scenario analysis will be based on a building stock model using probability distributions for demolition and renovation rates (Sandberg et al., 2014). Hopefully this will provide a better foundation for the scenario calculations compared to previous work. The aim of the scenario analysis is not to predict the future by projections showing the most likely development. Rather the scenario analysis will provide insight to possible future energy and emission development in the Norwegian dwelling stock and the third research question is defined as such:

Research question 3:

How may the implementation of different rehabilitation strategies influence the future energy demand and associated emissions in the existing stock of single-family dwellings built before 1980?

Calculating the energy consumption of the dwelling stock naturally induce many challenges, such as which energy to include in the analysis or how to estimate the likely technical level of the average Norwegian dwelling. Furthermore energy prices may influence the results of the economic analysis. In addition defining emission factors to be accredited the different energy carriers will also influence the results.

2 Literature

This section provides an outline of information regarding energy consumption and associated emissions, along with energy efficiency measures, all which will be further elaborated throughout this chapter.

Following is a brief overview of global energy consumption. Since the industrial revolution energy has increasingly been used in all aspects of the daily life. The global final energy consumption increased by 23% during 1990 – 2005. The most rapid increase was found in the service and transport sectors with 37%. Manufacturing industry, households and transport were the three end-use sectors consuming most energy in 2005, with 33%, 29% and 26%, respectively. Global energy use in the household sector increased with 19% between 1990 and 2005, and electricity and natural gas was found to be the main energy commodities used in OECD countries, providing 72% of total household energy requirements in 2005. (IEA, 2008)

Trends in CO₂-emissions are driven by the amount and type of energy use, as well as the indirect emissions associated with production of electricity. IEA (International Energy Agency) found that the global emissions of CO₂ from final energy use increased with 25% between 1990 and 2005. The most important sectors contributing to increasing emissions were manufacturing industry, transport and households. The latter accounted for 21% of global emissions experiencing an increase of 21% between 1990 and 2005, due to increase in final energy consumption along with changes to the energy mix.(IEA, 2008).

Energy saving measures are important to halt the increasing CO₂ emissions. The European Union has set a 20% cut in Europe's annual primary energy consumption compared to 1990 level as their goal for 2020. Several measures to increase efficiency at all stages of the energy chain have been proposed, and the measures focus on the public transport and building sectors(European Commission, 2013b).

Global GHG abatement cost curve beyond business-as-usual – 2030

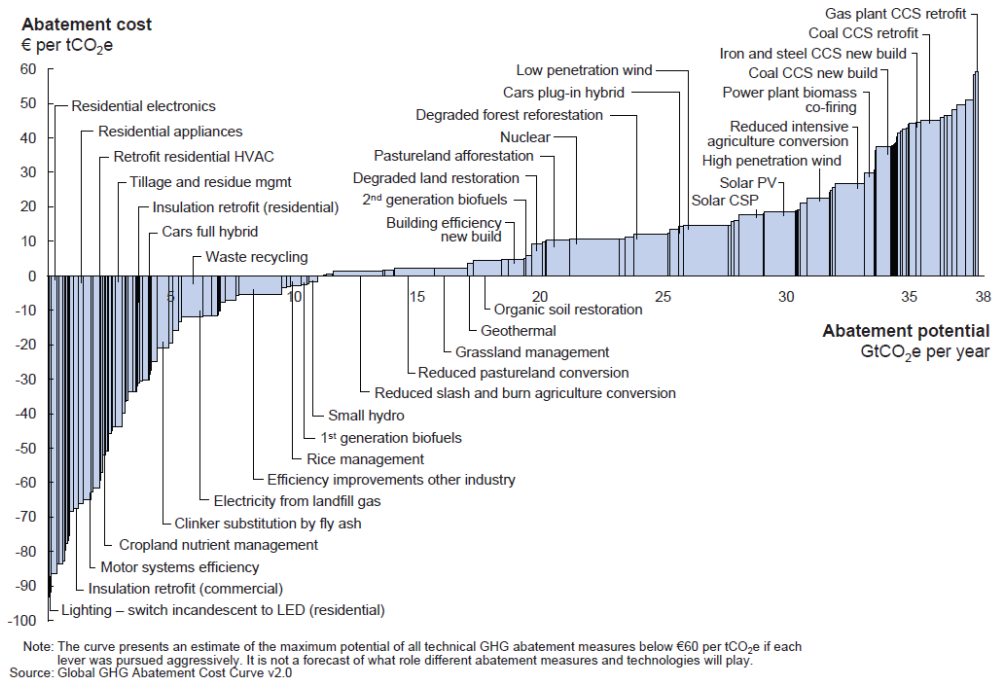


Figure 1: The McKinsey Abatement Cost Curve (McKinsey & Company, 2009)

Energy efficiency can contribute to significant reductions in energy consumption and emissions (IEA, 2014), and many measures for the building sector is seen as cost effective with current technology (DOKKA et al., 2009). This is often best described by the McKinsey abatement cost curve as seen in Figure 1. The left hand side shows the abatements that are cost effective, and as seen, many of these measures are related to residential systems (McKinsey & Company, 2009).

Similarly to the global society Norway has experienced a rapid increase of energy use during the last decades. Since 1976 the total end use in mainland Norway has increased by 40%. While the energy use in other sectors, such as transport, keeps its increasing trend, energy use in the building sector seems to be flattening since the end of the 90'ies. However, Energy demand in Norwegian buildings still counts for 37 % as seen by Figure 2 and reduction of energy consumption is assessed to have great potential. Measures such as improvements to the existing building stock and introduction of new technical building codes are deemed most effective.

(NVE, 2011)

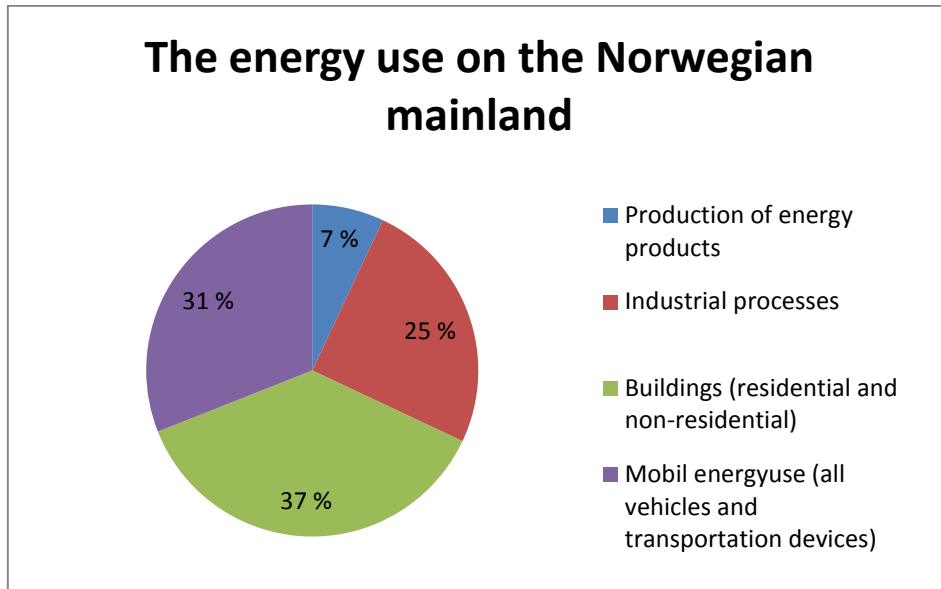


Figure 2: The Norwegian mainland energy use

A commonly used strategy for decisions related to energy efficiency measures in buildings is described by the Kyoto Pyramid, also known as Trias Energetica. The pyramid illustrates the important steps when reducing energy and which measures to be applied first. As Figure 3 illustrates the foundation of energy reduction in a building is to reduce the heat loss, suggesting that applying extra insulation or installing a balanced ventilation system should be the first step. Further, reduction of the electricity consumption, by measures such as energy efficient lighting and appliances should be considered. Better utilization of solar energy should also be prioritized before the energy source is selected (NVE, 2013). This selection should be based on renewable aspects as well as which sources are technically available in the area. For instance district heating should be chosen in larger cities, where a district heating network exists, while heat pumps and biomass based energy sources are better options for the districts (Lavenergiprogrammet, 2014).

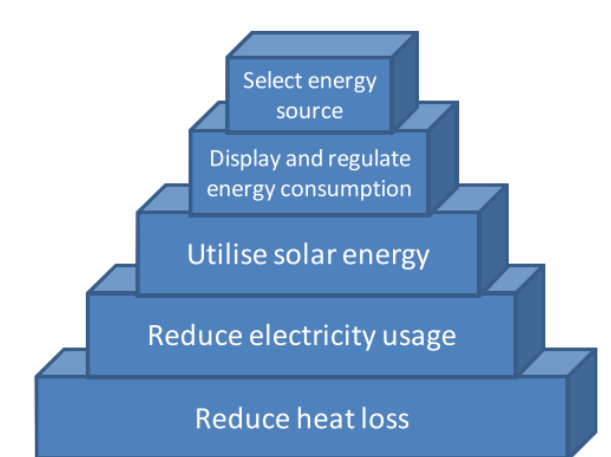


Figure 3: The Kyoto Pyramid (NVE, 2013)

2.1 The Norwegian building stock

Aggregated energy use in the building stock is closely related to the size of the stock itself (Sandberg et al., 2011). Hence, this chapter provides an overview of the historical development in the building stock, the current situation and some projections for the future stock.

2.1.1 Historical development and the current situation

The total area of the Norwegian building stock (BTA) has been estimated to approximately 385 million m², with 256 million m² in residential buildings and 129 million m² in non-residential buildings (Lavenergiprogrammet, 2012).

Mjønes et al. divided the Norwegian dwelling stock in three dwelling types, single-family houses, apartment blocks, and divided small houses. Further the stock was divided in the age cohorts, before 1956, 1956 – 1970, 1971 – 1980, 1981 – 1990, 1991 – 2000, and 2001 – 2010. They found that of the 2010 dwelling stock as much as 80% of the total dwelling area was built before 1990. 26% of the dwelling area was built before 1956, the cohort with the largest amount of dwelling area. Combined with little or no focus on energy conserving measures during the early 1900 and a large amount of single-family dwellings, consuming much energy, the saving potential for the stock was perceived as large.

Development of the dwelling stock

According to Bartlett et al. (1993) the share of detached single-family dwellings increased from 25% to 50% of the dwelling stock from 1960 to 1990. The same report stated that because of the rapid expansion of the dwelling stock 76% of the dwellings were less than 45 years old, and 38% less than 20 years old in 1990. In addition the rate at which new dwellings have entered the dwelling stock was found to have declined since the early 1970's (Bartlett, 1993).

The information from Bartlett et al. agrees with data found by Sandberg et al. in 2011. They found that the Useful Floor Area (UFA) was small and the construction activity low during the first half of the 20th century. Following the Second World War the construction activity increased due to an increase in the demand for floor area (Sandberg et al., 2011). Bartlett et al. found that the composition of new dwellings had changed as well. From 1986 to 1991, the share of new single-family dwellings entering the dwelling stock each year declined from 63 to 33%, while at the same time, the shares of semi-attached and attached single-family and multi-family dwellings increased from 25 to 41 % and from 7% to 19%, respectively (Bartlett, 1993).

Renovated building stock

Table 1: Renovations carried out on Single-Family dwellings (Mjønes et al., 2012)

Single – Family dwellings amount of renovations					
	Original building	Rehabilitated	Windows changed	Extra insulation wall	Extra insulation roof/floor
> 1956	9%	91%	74%	64%	55%
1956 – 1970	24%	76%	64%	32%	44%
1971 – 1980	61%	39%	35%	6%	20%
1981 – 1990	83%	17%	12%	3%	14%
1991 - 2000	95%	5%	4%	3%	2%
2001 - 2010	100%	0%	0%	0%	0%

According to Mjønes et al. 52 % of the total dwelling area was found to have undergone energy renovation to varying extent. Just below 50% of all residential buildings have been energy renovated. As may be expected, most of the energy rehabilitations have been carried out in older dwellings, and mostly during the recent decades. Enova explains this with an increased standard of living with higher incomes, the buildings condition, government requirements as well as increased knowledge. In addition they found that window replacements dominated the energy related rehabilitations. The report states that for single-family dwellings 74% of those built before 1956 had upgraded windows. This amount was at 64% and 35% for those built during 1956-1970 and 1971-1980, respectively. Windows are subjected to the most visible wear and tear in addition to being the easiest replacements technically, which might explain the frequent replacement. Enova also defined measures to rehabilitate dwellings to TEK 10 standards. This was defined based on the Energy Framework requirement as defined by TEK 10 as well as the level of difficulty of rehabilitating the dwellings.

(Mjønes et al., 2012)

2.1.2 Future development

The future energy demand in the building sector will be dependent on both the energy intensity and the development of the future dwelling stock. Hence, studying future energy demand requires some assumptions regarding the future development of the dwelling stock itself. Therefore this section provides an outline of how the dwelling stock might change over the next decades.

Sartori et al. for instance assumed the building stock to increase linearly for the next decades as it has for the past ones. The assumption was based on statistics estimating a nearly linear population growth for the coming decades. The flow of new construction was therefore set approximately at the same level as experienced during 1996 – 2005, corresponding to 1% of the 2005 stock, for the dwelling sector. The demolition rate was set to 0.2% of the reference stock (2005) based on the scarce information available. The renovation rate was found to be even more difficult to obtain and therefore three levels, all held constant throughout the period of analysis was investigated. (Sartori et al., 2009)

Multiconsult estimated the future Norwegian building stock based on different literature sources. The rate of new construction, rehabilitation and demolition were all held constant at 1.33%, 1.5% and 0.6% respectively. The rehabilitation rate was found to be subjected to large insecurities both with regards to the number of buildings being renovated and how renovation was defined. Multiconsult also questioned the rate of demolition arguing that it was an overestimation. Based on these assumptions the future development of the building stock was estimated as depicted in Figure 4. (Multiconsult et al., 2011)

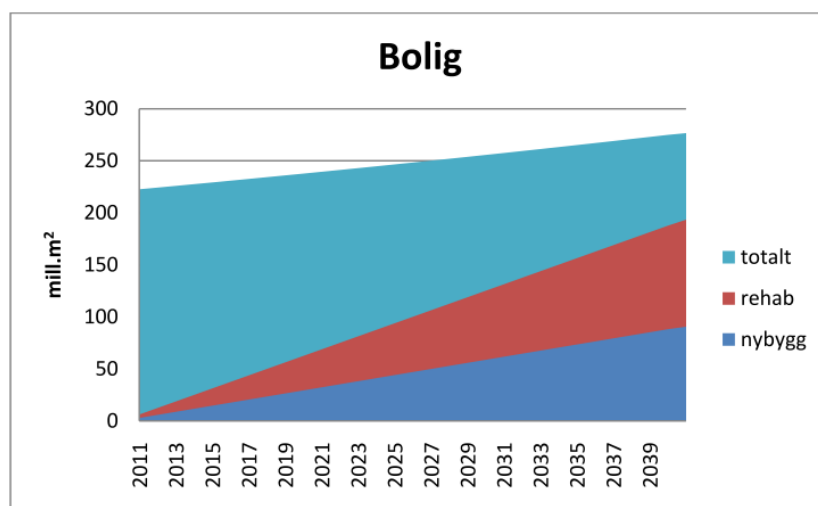


Figure 4: Future dwelling stock development estimated by (Multiconsult et al., 2011)¹

In general it seems that most studies estimating the development of the future dwelling stock base the rate of new construction on the historical rate, while the rehabilitation rate is based on other sources and assumed constant at 1.3 – 1.5 %. The rates used are frequently discussed as subjected to insecurities (Multiconsult et al., 2011). This also seems to be the field consensus; the rates are difficult to estimate.

¹ English translation: Bolig = Dwelling, Totalt = Total, Rehab = Rehabilitation, Nybygg = New constructions

2.2 The energy situation in the Norwegian building sector

This chapter provides an introduction to the energy situation in the Norwegian building sector. The historical development and the current situation are described. In addition some projections for the future energy consumption are outlined.

2.2.1 Historical development and the current situation

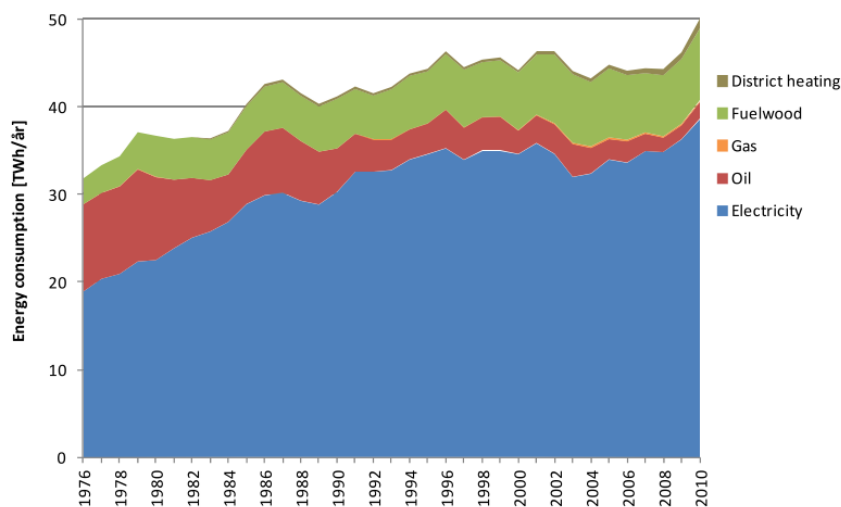


Figure 5: Household energy consumption, 1976 – 2010 (NVE, 2013)²

Currently the Norwegian building stock consumes approximately 83 TWh, distributed as 46 TWh consumed by residential buildings and 37 TWh by non-residential buildings. Following a rapid increase during the previous decades, since the mid 90's buildings have experienced a tendency of flattening energy consumption, i.e. Figure 5. This is often explained by a reduced growth in floor area, energy efficiency measures, and climate change giving higher outdoor temperatures. (NVE, 2013)

In 2011 an average Norwegian household consumed approximately 21 000 kWh/year. A breakdown of this energy use revealed that 66% was used to cover space heating, 22% for electricity-specific energy consumption while 12% was used for water heating. (NVE, 2013)

² The spike in energy use in year 2010 can be explained by the very cold winter of that year. With temperature correction of the energy use the trend of flattening energy consumption was evident for year 2010 as well.

Literature review

Sandberg et al. studied energy use in the Norwegian dwelling stock and found that the aggregated Norwegian dwelling stock consumed a total of direct and indirect energy increasing from 23 to 45 TWh during 1960 – 2004. This increase happened despite a 39% decrease occurring in the specific energy consumption in the use phase, and was therefore explained by an increasing stock. The total energy consumption in the dwelling stock was heavily dominated by the use phase, while the upstream and downstream processes were found to have little impact. This was explained by factors such as the long lifetime of Norwegian buildings and the cold climate, coupled with high indoor comfort temperature (Sandberg et al., 2011).

Mjønes et al. estimated the energy use in the dwelling stock and found the annual total energy use in Norway to be 45.2 TWh in 2010. The numbers were compared to SSB and were found to be an overestimation of 3.5% when holiday houses had been subtracted. They found the net energy demand for buildings as described Table 2 (Mjønes et al., 2012).

Table 2: Energy demand for Single-Family dwellings (Mjønes et al., 2012)

Age cohort	Total net energy [kWh/m²]	Net energy need for space heating [kWh/m²]	Net energy need for lighting [kWh/m²]	Net energy need for electrical appliances [kWh/m²]	Net energy need for fans [kWh/m²]	Net energy need for DHW [kWh/m²]
> 1956	256.6	197.8	11.4	17.5	-	30.0
1956-1970	180.4	121.5	11.4	17.5	-	30.0
1971-1980	146.6	87.8	11.4	17.5	-	30.0
1981-1990	140.3	80.7	11.4	17.5	0.7	30.0
1991-2000	130.5	70.9	11.4	17.5	0.7	30.0
2001-2010	125.8	62.0	11.4	17.5	0.7	30.0

2.2.2 The current situation regarding energy supply to buildings

Energy demand in buildings can be covered using various technologies. In this section the most common technologies and carriers are summarized along with a description of future possibilities.

As can be seen from both Figure 5 and Table 3 there has been a gradual change in the heating carriers used in Norwegian households during the last decades. In earlier years most of the heating was based on solid fuels, while the current dwelling stock is heavily dependent on electricity, c.f. Figure 5. Norwegians are amongst those consuming most electricity per

inhabitant, with an average consume of 16 000 – 18 000 kWh per household. As much as 77% of the energy use in households is covered by electricity. Electricity has historically speaking been very cheap in Norway compared to other countries. However, in recent years the electricity price for households has increased. The fixed cost increased by as much as 60% during 2000 – 2011. This has not induced a conversion to other heating carriers however, as the price of petroleum products and district heating experienced a similar increase. However, the increase in energy prices seems to have resulted in increased investments in energy efficiency measures. At the start of the new millennium for instance Heat Pumps were hardly used in the Norwegian dwelling sector. In 2009 they had been implemented in 18.5 % of the households. (Bøeng and Holstad, 2013)

Table 3: Distribution of the most important heating carrier in Norwegian dwellings (Bøeng and Holstad, 2013)

Years	Central heating ³	Direct electric heating	Heat Pump	Liquid fuels	Solid Fuels
1960	10 %	16 %		6 %	68 %
1967	9 %	29 %		21 %	41 %
1973	13 %	27 %		39 %	21 %
1980	14 %	39 %		23 %	24 %
1993 – 1995	10 %	65 %	0	5 %	19 %
2001	7 %	69 %	0	6 %	18 %
2004	8 %	62 %	3 %	5 %	22 %
2009	8 %	55 %	15 %	2 %	19 %

District heating

District heating is not widely in use in Norway today, although it is increasing. In 2010 the annual production of district heating amounted to 5.2 TWh, an increase of 18%. In addition district heating has been developed, or are being planned in 92% of all cities with more than 10 000 inhabitants (Fjernvarme.no, 2014). According to Enova the annual district heating delivered in 2019 is estimated to at least 7,3 TWh (Enova, 2012). Even if district heating is an increasing energy source for dwellings in Norway it's still quite an underdog. Only 2% of Norwegian dwellings used district heating as their main source of space heating in 2009 (SSB, 2011).

³ District heating is included in these numbers.

Biomass

Biomass for space heating has long traditions in Norway. In recent decades, mainly as wood fired stoves used to cover peak load. Biomass can also be used as an alternative to the common direct electricity based heating, for instance through biomass boilers using pellets, a product made from compressed wood chippings. Biomass boilers can cover both space heating and domestic hot water heating. In addition the use of bio-pellets is seen as environmentally friendly and often referred to as CO₂-neutral, although this can be debated, as can be found in chapter 2.9. However, in large cities using pellets, which is associated with particle emissions, can be detrimental to the air quality (Boligvarme, 2014a). Another negative aspect is that the technology requires more maintenance compared to other space heating technologies, as well as an added space demand, as the pellets have to be stored (Boligvarme, 2014b).

Heat pumps

A heat pump utilize the energy in ambient air, sea water or the ground to heat either air or water for space heating. It's an old technology based on thermodynamic principles' of temperature and pressure in the working fluid. For further technological information the interested reader is referred to (Stene, 1997)

The most common Heat Pump in Norway is the air-to-air heat pump, utilizing ambient air as the heat source and heating the indoor air directly (Varmepumpeinfo, 2012a). Utilizing ambient air has both benefits and drawbacks. On the positive side it's an easily accessible resource, and there are no costs with drilling or digging into the ground, as with ground source heat pumps. On the other hand the air temperature and the space heating demand have an opposite correlation. The temperature decrease when the space heating demand is at its largest. The heat pump therefore has to be combined with another technology to cover peak load.

If the building has a waterborne space heating system an air-to-water heat pump can be used. This heat pump can cover both space heating and domestic hot water demand, in combination with another technology covering peak load (Varmepumpeinfo, 2012b).

PV-panels and solar collectors

The energy radiation upon earth is thousand folds the total human energy demand, and thus, the utilization of solar energy has huge possibilities. The sun supplies the Norwegian building stock with 3 – 4 TWh/year of passive solar heat through the windows. However, the annual

solar radiation varies quite extensively throughout the year and across the country, with 700 kWh/m² in the north and 1100 kWh/m² in the south. (Solenergi.no, 2014a)

Photo Voltaic panel or solar panel is a technology converting solar radiation to electricity (Solenergi.no, 2014b). According to a study performed by Multiconsult the typical Norwegian roofs, with their angle, is very well suited for mounting PV-panels. The angle is normally quite close to the optimal angle, and most buildings have a larger part of their roof area facing toward south, achieving good conditions for solar technologies (Multiconsult, 2013).

Even if Norway plays a role in the global PV-industry, the technology has not been widely implemented within the country itself. The total electricity production from PV-panels is estimated to be 8.7 MW. However, this number is subjected to some insecurity. Solar panels are mainly used in remote parts of the country where the electricity grid for some reason is not an option, and thus are mainly used for cottages or boats (KanEnergi and SINTEF Byggforsk, 2011).

2.2.3 The future development

This section outlines three studies providing scenario analyses for the future energy development in the Norwegian dwelling stock.

Thyholt et al. studied the Norwegian building stock and calculated possible future energy scenarios. The base-scenario showed a linear increase in the energy demand approximating 55 TWh in 2035 (Figure 6. Energy efficiency measures such as conservation measures or upholding the energy requirements given by EPBD for both renovated and new buildings could reduce the future energy consumption. Conservation measures were found to reduce the energy consumption in 2035 with as much as 10 TWh compared to the base-scenario.

(Thyholt et al., 2009)

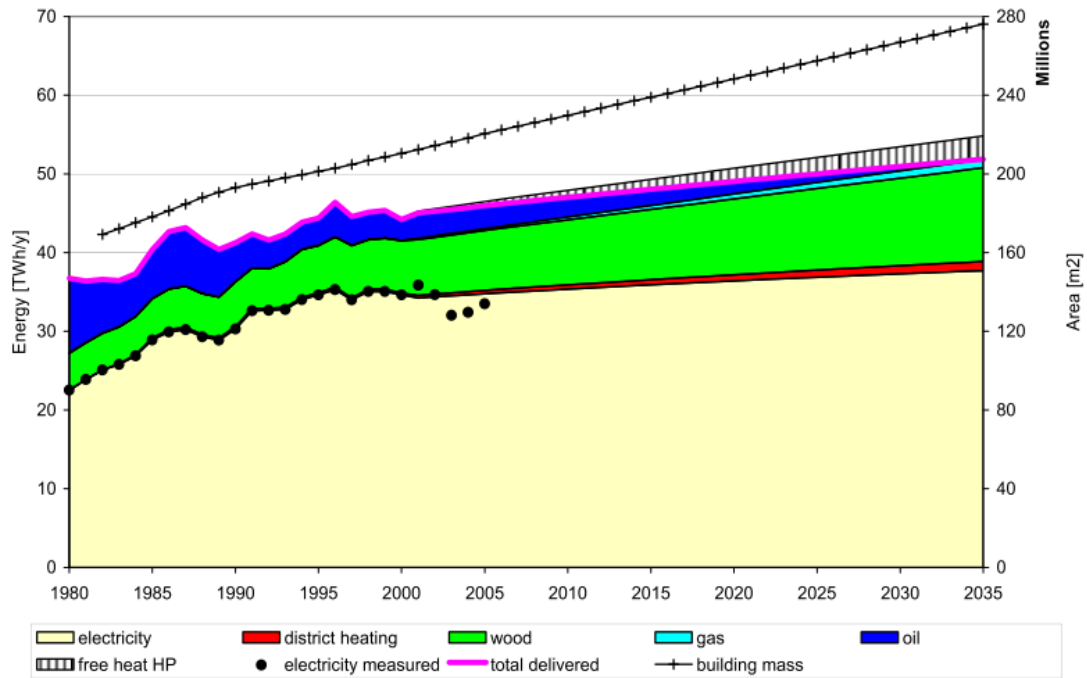


Figure 6: The base-scenario as calculated by (Thyholt et al., 2009)

The total future energy demand was calculated by Sandberg and Brattebø, based on a set of assumptions regarding future energy intensities for space heating, water heating, appliances and materials. According to the results the total energy demand is likely to increase substantially during the coming decade before leveling off following year 2030. Furthermore the results indicated a 20% increase in direct energy demand from 2005 to 2035.

(Sandberg and Brattebø, 2012)

Sartori et al. studied the energy situation in Norwegian buildings and calculated projections towards 2035. The heating carriers share was derived by combining information on delivered energy, net energy demand and system efficiencies. The values observed during 1996 – 2005 were averaged, and the trend observed during this period was continued linearly until year 2035. If the observed trend was to continue, the changes would be largest in the non-residential sector. The use of direct electricity will be more than halved by 2035, while district heating and heat from heat pumps will become nearly as important as direct electricity. The use of gas will decrease and oil will almost be phased out. In the residential sector the direct use of electricity will keep its position as the most significant energy carrier, although with a smaller share. The use of wood and heat pumps will increase considerably, while gas and district heating will only be used to a marginal extent. The oil use will be completely phased off by 2035.

(Sartori et al., 2009)

2.3 Political context

There exist many political acts regulating the construction of buildings and their energy use. As the legislation in Norway is influenced by regulations in the EU through the European Economic Area (EEA) agreements this chapter will focus on regulations on both the EU and Norwegian level.

2.3.1 European energy directives

The European Union is committed by the Kyoto agreement to reduce the overall greenhouse gas emissions by at least 20 % below 1990 levels within 2020 (European Commission, 2014), and has consequentially introduced many legislative instruments to uphold their commitments. In the following sections the three most important instruments regarding energy consumption in buildings are summarized.

The Energy Performance of Buildings Directive (EPBD) implemented in the EU in 2002 as Directive 2002/91/EC (European Parliament, 2002) is one such instrument focusing on reducing the energy demand in the building sector. The Directive was adopted in 2010 based on experiences and a detailed impact assessment and is currently termed Directive 2010/31/EC (European Parliament, 2010). Under this directive the Member States must “establish and apply minimum energy performance requirements for new and existing buildings, ensure certification of building energy performance and require regular inspection of boilers and air conditioning systems in buildings.” The Directive also requires the Member States to ensure that all new buildings are nearly Zero Energy Buildings by 2020. In addition the member states shall set targets which stimulate the transformation of buildings that are refurbished into nearly Zero Energy Buildings (European Commission, 2013a).

The EU adopted a directive on energy efficiency on the 25 of October 2012, Directive 2012/27/EU, most of which must be implemented during June 2014.

“This directive establishes a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Union’s 2020 20% headline target on energy efficiency and pave the way for further energy efficiency improvements beyond that date.”(European Commission, 2013c)

The directive set rules to remove barriers in the energy market as well as overcome market failures that impede efficiency in the supply and use of energy. In addition it provides an establishment of indicative national efficiency targets for 2020 (European Commission, 2013c).

In 2009 the EU adopted the Directive on the Promotion of the use of Energy from Renewable Sources (RES Directive), setting the target that 20% of EU's energy consumption in 2020 shall be covered by renewable sources. It sets mandatory national targets for the overall share of RES in gross final consumption of energy for each Member State (EREC, 2012).

2.3.2 Norwegian regulations and political measure

Norway has committed to reduce the GHG emissions by 30% of 1990-level by 2020. Within 2050 Norway shall be carbon neutral. As calculated by KLIF⁴ the realistic reductions are estimated to 13 – 16 million tons CO₂ equivalents compared to the reference path as projected in 2007. (Regjeringen.no, 2012)

Building codes and standards

The first nationally implemented building code in Norway came into act in 1965. In the prior years the building code had only applied to cities and some specific parts of the country side (Regjeringen, 2003). Since then many new and revised building codes has been enforced. Currently the main legislative instrument concerning buildings is the technical regulations, termed TEK.

The first technical regulation, called TEK 97, was implemented as a regulation of the 1987 act, in 1997 (Lovdata, 1997). The energy requirements in the Norwegian building regulations where revised in 2007 following the implementation of the EPBD in Norway. It was further revised in 2010 when the EPBD was fully implemented (DIBK and NVE, 2012), with the current technical regulation, TEK 10, authorized in the plan and building act of 27 July 2008(Lovdata, 2010).

The Norwegian Parliament has agreed that all new buildings should be at passive house level by 2015 and the definition of the coming minimum is currently under development(DIBK 2012). Currently no national standard or definition exist for nearly Zero Energy Buildings in Norway (Rambøll, 2013).

The RES Directive was implemented in the EEA-agreement in 2011 and Norway has agreed to a goal of 67.5 % renewable energy within 2020. Norway has the highest percentage target in Europe because of the high share of renewables already in use in Norway (Bøeng and Holstad, 2013).

⁴ Klima og Forurensningsdirektoratet (the department of climate and pollution)

Technical regulation, TEK 10

The requirements of TEK 10 are summarized in Appendix A.

Chapter 14 of TEK 10 is dedicated to energy and energy measurements. §14-1 states that all buildings shall be designed and constructed in such a way that low energy requirement and environmentally energy supply is promoted.

There are two ways of achieve the energy efficiency requirements of TEK 10 as stated by §14-2. The building can either achieve the required levels of §14-3, defined as the Energy Measure method, or have a total net energy need, including the energy need for electrical appliances and lightning, lower than those given in §14-4, referred to as the Energy Framework method. Either way the building must achieve some minimum requirements as stated in § 14-5.

Buildings with an area less than 30 m^2 are exempted from these rules except §14-5 first section. §14-3 gives requirements on building parts as U-values on walls, floors, window etc., as well as the infiltration and ventilation heat losses and temperature efficiency of the ventilation system. §14-3 (2) however, states that for dwellings the energy measures concerning U-values and infiltration and ventilation heat losses can be deviated from as long as the heat loss number doesn't increase.

§14-3 also requires a yearly average temperature efficiency of ventilation heat recovery for dwellings at 70%, while §14-7 require all buildings with a heated BRA less than or equal to 500 m^2 to be performed such that at least 40% of the net space heating demand can be covered by other energy carriers than direct electricity or fossil fuel.

(TEK10, 2010).

Norwegian Standard NS 3031

All the relevant requirements of NS 3031 are summarized in Appendix A.

The Norwegian Standard NS 3031 describes how to calculate the energy performance of buildings. It has been revised twice, the last time in 2011. This revision was done to complement the European standards on energy performance of buildings, by using the rules of these normative references, but basing the calculations on national values.

The standard defines how to calculate total net annual energy demand for a building, including energy needed for space heating, space cooling, domestic hot tap water (DHW), fans, pumps and lighting. The standard also provides standard values for energy need for lights and technical requirements in table A.1. The values have been developed to be used for control calculation against official requirements and thus do not necessarily reflect the real world conditions.

The annual energy demand for lighting and technical equipment has been found as the mean power requirement during the time of utilization multiplied with the utilization time. As described in Appendix A the net energy need for space heating includes heat recovered from the ventilation air, but does not include heat gains from the domestic hot water system. It should be mentioned that the standard distinguishes between net energy need for space heating and total net energy need, the latter including energy needed for electrical appliances lighting and so on.

(Norsk Standard, 2011)

Norwegian Standard NS 3700

The requirements of NS 3700 has been summarized in Appendix A and are all for the category Passive House.

The Norwegian standard NS 3700 is based on NS 3031, and describes the requirements for Passive Houses and two types of Low Energy buildings. It applies both for new buildings and the renovation of buildings to passive house standard.

Passive Houses are known as environmentally friendly buildings with a good indoor climate and extremely low energy need. This standard defines such passive houses and takes into consideration the Norwegian climate, construction methods and traditions. The standard sets requirements for maximal heat loss, net energy needed for space heating, type of energy supply and constructional elements, as well as the annual efficiency for the ventilation heat

recovery system. It should be noted that this standard has a requirement on the net energy need for space heating, which doesn't include energy needed for electrical appliances and lighting. The standard also set a requirement on the amount of energy delivered that may come from direct electricity or fossil fuel.

As stated in the standards chapter 4.4 the total energy delivered from direct electricity or fossil fuels shall be less than the total net energy demand minus 50 % of the net energy need for DHW.

In addition to the requirements the building envelope must fulfill the minimum requirements stated in TEK 10. A building that meets the minimum requirements does not necessarily manage the requirements on heat loss and net energy need. Therefore the standard also gives some typical u-values used for Passive Houses, also summarized in Appendix A.

(Norsk Standard, 2013)

2.4 Terms and definitions of energy

Comparing different energy demands calculated based on different system boundaries is often described as comparing apples to oranges. Hence a clarification of the terms and definitions of system boundaries and energy is needed.

A building requires energy in all phases of its lifetime, from construction, during use and finally when demolished. Taking all the energy use over the entire lifetime into account requires an LCA (Life Cycle Analysis). The total life cycle energy is the sum of the embodied energy, the operating and the demolition energy. Embodied energy is defined as the energy utilized during the construction/manufacturing phase, including the energy content of all the materials used in the building and its technical installations as well as the energy use occurring during construction and renovation. Operating energy is the energy required to maintain the comfort conditions and day-to-day maintenance of the building. The demolition energy is the energy required to demolish the building as well as transporting the waste material to landfill sites (Ramesh et al., 2010).

Most literature available for energy demand in the building sector concerns the operating energy use, further elaborated in chapter 2.5. The operating energy can further be divided into sub energy uses defined by different system boundaries. For instance the energy demand can be divided into the delivered and the net energy demand. The distinction is that the delivered energy demand takes into account the system efficiencies of the energy supply system.

The requirements of different standards are often based on different energy demands. The Energy Framework method described in TEK 10 for instance, is based on total net energy

need. This is the net energy demand for the building, energy use for space heating, domestic hot water heating, lighting and electrical appliances. However, the system efficiencies are not taken into account. The Passive House requirement only relates to the net energy demand for space heating and DHW, while NS 3031 provides the calculation procedure for both net and delivered energy demand.

Primary and secondary energy is yet another definition of energy. When the standards set energy requirement it's related to the secondary energy, the energy every household have in their electrical outlet. However, this doesn't take into account that energy is needed to produce the energy delivered to the households.

Primary energy is defined as:

“(..) energy that has not been subjected to any conversion or transformation process”

“Primary energy includes non-renewable energy and renewable energy. If both are taken into account it can be called total primary energy”

“For a building, it is the energy used to produce the energy delivered to the building. It is calculated from the delivered and exported amounts of energy carriers, using conversion factors.”
(Norsk Standard, 2008)

As can be seen from the definition primary energy can be divided in two concepts, including or not including the renewable component. When establishing the primary energy factor used to converse the delivered energy to primary energy the renewable component may or may not be included, leading to different primary energy factors. Therefore the primary energy factor when considering renewable resources can be lower than 1 (Aalerud, 2012). The system border thus plays a vital role also when considering the concept of primary energy. An in depth analysis of primary energy is however beyond the scope of the current work. The interested reader is referred to the MSc Thesis of Petter Johan Aalerud which provides a good introduction to the concept (Aalerud, 2012)

2.5 Energy efficient buildings

This chapter provides an overview of the terms and definitions that are related to energy efficient buildings, as well as an extensive literature research into this major field.

2.5.1 Definitions

There exists a vast landscape of terms and definitions of energy efficient buildings, such as Low Energy Buildings, Passive Houses, nearly Zero Energy buildings, nearly Zero Emission Buildings, net Zero Energy buildings and net Zero Emission Buildings. This chapter will provide an overview as well as state the definitions used throughout the current work.

According to Sesana and Salvalai the historical definitions of zero energy are mainly based on annual energy use for the building's operation. The term "net energy" is used to describe a balance between energy used by the building and energy produced by its renewable systems. This definition is not entirely in line with the original term of net energy as it is used in the field of ecological economics, which relates to the whole life cycle energy accounting. The term "net zero energy building" is frequently used to describe a grid connected building which over the year has a net zero energy balance between the energy consumed and produced at the building, without considering the energy required to deliver the building and its components. (Sesana and Salvalai, 2013)

The Arnstad group interpreted the term "nearly zero energy buildings" as a building achieving the energy requirements of the Passive House level where approximately all of the delivered energy was based on renewable sources. (Arnstad et al., 2010)

Graabak and Feilberg defined both zero energy and zero emission buildings (ZEB) in their work.

"Conceptually, a zero energy building is a building with greatly reduced energy demand, such that the energy demand can be balanced by an equivalent generation of electricity (or other energy carriers) from renewable sources. In a zero emission building such balance is achieved not directly on the energy demand and generation but on the associated CO₂ equivalent emissions." (page 6(Graabak and Feilberg, 2011))

The recast of the EPBD defines nearly Zero Energy Buildings as such:

"A "nearly zero energy building" is a building that has a very high energy performance(...). The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby." (Article 2 (European Parliament, 2010))

The EPBD definition leaves room for interpretation and was established as such, acknowledging the very varying conditions and construction methods among the member states. Member states are required to draw up their own plans designed for their country's climate (Bogdan et al., 2011). These plans shall include definitions of nearly zero-energy buildings, reflecting the national, regional or local conditions and including a numerical indicator of primary energy (European Parliament, 2010).

The interpretation of nearly zero-energy varies among different countries and standards. In addition the border for which type of energy and energy use to be included varies. According to the EPBD for instance only the energy use for heating, cooling ventilation and lighting is to be considered in the nearly zero-energy definition. The system border as well as the type of energy considered is also of crucial importance when defining a Zero Energy Building (Bogdan et al., 2011).

The Buildings Performance Institute Europe (BPIE) has established three main principles which a proper nZEB definition should rest upon. First there should be a clearly defined boundary for the energy flow related to the operation of the building. BPIE suggests this boundary to be the energy need of the building, the sum of useful energy need for space heating, space cooling and domestic hot water (for dwellings), including the distribution and storage losses, i.e. the delivered energy demand. Second, there should be a clear definition of how to calculate or measure the renewable energy share including a clear guidance of how to assess this share. The eligible share of renewables is suggested as all energy produced from renewable sources on site, including heat pumps. The third principle relates to the primary energy demand and CO₂ emissions and states that the primary energy and CO₂ emissions should be calculated and there should be a clear guidance on how to assess these values. (Bogdan et al., 2011)

For the current work Passive Houses will be defined accordingly to NS 3700. A net Zero Energy building is a building where the energy balance over the year equals zero. The energy considered will only be the energy demand to operate the building during a year, thus the life cycle energy demand including energy for construction and demolition will not be taken into account. To distinguish between Zero Energy Buildings and Zero Emission Buildings, the first will hereby be termed ZEnB, while the latter accordingly to the citation above will be termed ZEB.

2.5.2 Literature review

There exists a great variety of studies concerning the energy use in buildings and the implementation of energy efficient measures. This chapter provides an overview focusing on studies performed for the Norwegian building stock. First two studies are shortly rendered giving an introduction to many aspects related to energy efficient buildings. Thereafter subsections provide an in-depth review of three studies relevant for the current work. As there

is currently such a large amount of information regarding this subject, this is by no means a complete overview of all information available.

Sartori and Hestnes analyzed 60 houses during an extensive literature review and found that the operating energy represents by far the largest part of energy demand in a building during its life cycle. Low-Energy buildings were found to have larger embodied energy than conventional ones, but the total energy demand was consistently lower. When comparing a Passive House to a conventional one it was found to require approximately the double of embodied energy, while the total energy was reduced by a factor of three. In conclusion reducing the demand for operating energy was found to be the most important aspect for designing energy efficient buildings throughout their lifetime.(Sartori and Hestnes, 2007)

Risholt and Berker performed a case study of Norwegian privately owned single-family houses from the period 1980 – 1990. The energy efficiency status of 102 dwellings was mapped. In addition the technical condition and home upgrade status of 91 houses were analyzed and categorized based on visual examination. Furthermore the energy efficiency data of eleven buildings were studied through a detailed analysis of the technical condition of the houses, the dwellers energy behavior, their renovation decision processes and their experiences from renovation.

The results obtained by Risholt and Berker indicated that the real life energy use numbers are lower than those obtained from nominal calculations. This was attributed to lower real life indoor temperature in bedrooms as well as the values set by NS 3031 for air exchange rates and DHW being too high. In addition the homeowners' attitude was found to be of importance. One of those asked had installed an air to air heat pump and had experienced annual electricity saving of 8000 kWh, but his willingness to do rehabilitations on the building envelope to reduce the heat loss was low. In conclusion the behavior and practices of the homeowners were found to have major importance for the energy use in dwellings, as well as their understanding of energy saving measures.

(Risholt and Berker, 2013)

The Workgroup for energy efficient buildings established by KRD⁵

In 2009 a workgroup was established by the ministry of regions and municipalities to provide input to the upcoming plan of action for energy efficient buildings. Two realistic energy reduction targets for the coming decades were described. Within 2020 the realistic reduction for the entire stock was estimated to 10 TWh/year, reducing the annual energy demand from 80 TWh – 70 TWh. Further reduction to 40 TWh/year in 2040 was deemed possible.

Based on the current annual rate of new buildings, 1.2%, as much as 80% of the reduction within 2020 must be carried out in the existing building stock. To achieve the reduction target for 2040 however the focus must be on buildings constructed during 2010 – 2040, since 37% of the 2040 building stock will be constructed during this period. Therefore, the more energy conserving measures applied to new constructions, during this period, the more likely achieving the 2040 target becomes.

In order to achieve the 2020 goal the energy demand in 85% of those buildings likely to be fully⁶ renovated must be limited to 160kWh/m². Furthermore, for the remaining 15 % the energy demand must be limited to even less, 100kWh/m². Similarly the energy demand in rehabilitated buildings during 2020 – 2025 must be limited to 70kWh/m² and 30kWh/m² by 2040.

Private owners account for 50% of the existing building stock. Thus 2.8 million decision makers must be convinced to invest in energy efficient measures. Hence for the largest part of the building stock full renovation is not likely to be carried out due to the costs associated with such renovations.

Pilot projects have shown that Nearly Zero Energy Buildings are achievable with the current technology. However, the current energy system was found not to be prepared for a widespread implementation of such buildings as they require energy being produced on site along with trading of energy with the grid. Therefore planning an area of buildings rather than just planning single energy efficient buildings was pointed out as a better solution. Furthermore additional research was called upon to investigate the future energy efficient possibilities for the building sector.

(Arnstad et al., 2010)

⁵ KRD: “ The Norwegian ministry of municipalities and regions”

⁶ Fully renovated was defined as renovations where the cost amounted to more than 25% of the buildings total value.

Potentials for and barriers against Passive Houses and nearly Zero-Energy Buildings

A study provided by Rambøll AS and Xargia AS considered the potential for and the barriers against Passive Houses and nearly Zero Energy Buildings in Norway. The main goal was to map the realistic energy efficiency potential of new buildings, as well as Passive House renovation of the building stock during 2020 – 2040.

Three different potentials were investigated. The technical potential, described as the technically achievable level disregarding all economics. By taking the Life Cycle Costs under consideration the technical level was further developed into the economic potential. Finally, by investigating other factors in addition to the economic ones, the market potential was found.

When carrying out the analysis Passive Houses were defined according to the Norwegian standard NS 3700 (Norsk Standard, 2013), and nearly Zero Energy Buildings (nZEnB) according to (Arnstad et al., 2010). In addition three rehabilitation standards were defined, “rehab TEK 10”, “rehab passive” and “rehab nearly zero”, taking into account that rehabilitated buildings are not guaranteed to manage the requirements perfectly.

The nZEnB was reached by combining a Passive House with an energy supply system including a Heat Pump and a solar collector. PV-panels or wind mills for electricity production were discussed as possible measures to produce the electricity needed for the Heat Pump and thus ensuring a nZEnB. However, the authors saw these as expensive, especially for smaller units such as for dwellings.

Two types of measures were investigated, passive and active ones. Passive measures are such measures which reduce the energy demand of the building, such as applying more insulation or changing the windows, as well as installing mechanical ventilation or low energy lighting. The active measures are related to the energy supply system, and include measures such as changing from a direct electric heating system to a heat pump.

The total technical potential for energy savings was calculated to 5 TWh in 2020 and 15 TWh in 2040, both compared to TEK 10 level. The potential for energy savings was almost equally divided between measures in new buildings and rehabilitated ones. Four categories of passive measures seemed to have most effect; better air tightness, heat recovery, ventilation air flow and changing windows and doors. Active measures such as heat pumps would induce largest savings in rehabilitated buildings, compared to new constructions, because new buildings require less energy in the first place. The active and passive measures investigated would give approximately the same energy savings, and both would induce large savings in dwellings because of the vast floor area belonging to the category.

The economic analysis showed that increasing energy prices both increased the economic and market potential. Furthermore the economic barriers were found to be larger for rehabilitation

of buildings than for new constructions, and the barriers were most influential for dwellings, reducing the economic potential significantly.

The main conclusion was that there exist real barriers for managing both Passive Houses and nearly Zero Energy Buildings. Three main barriers for Passive Houses were found; the lack of belief in the profitability of such projects, the accessibility of materials for rehabilitation, and the increased need for better organization and cooperation across different fields. The realistic market potential, factoring in such barriers, was found to be almost half of the economic potential.

The active measures were found to be less attractive than the passive ones, leading to the conclusion that an evolution towards nZEnB is unlikely if the Passive House standard is introduced as the new requirement. However, the authors believed the potential for the active measures to be underestimated. Additionally the result indicated that reducing the insecurities of the decision makers by better information will trigger the potential in the same way as better financial support systems. Moreover, a combination of informative and financial measures coming from the governmental level will most likely have great impact.

(Rambøll AS and Xrgia AS, 2011)

Energy demand in the Norwegian building stock: Scenarios on potential reduction

Sartori et al. developed a model for studying the effect of three hypothetical approaches for reducing electricity and energy demand in the Norwegian building stock. The approaches studied were, wide diffusion of thermal carriers, heat pumps and conservation measures, and combinations of these measures.

In this model energy demand was calculated by the product of activity and intensity matrices. The intensity properties were defined in archetypes being the result of different energy classes and heating carriers share options. The activity levels for the stock were defined for new construction, renovation, and demolition flows. When determining the likely future stock increase historical data were used. Historically both the residential and the service sector experienced a nearly linear increase corresponding to a nearly linear increase in population during the same period. The projection for the Norwegian population growth is linear as well, hence the stock was expected to continue its linear growth, and the flow of new construction was set approximately equal to that of the observed period. Data for the demolition rate was harder to come across. The authors based their study on data provided by other literary sources and it was set to 0.2% of the reference stock of year 2005. The renovation rate was based on a former study by (Sartori et al., 2008) and three different levels were applied to the model to test its sensitivity to this parameter.

The basic assumption was that a consistent and enduring change in the net energy demand of a building can be achieved only when a building undergoes major renovation. Therefore a

building was assumed to be represented by a certain energy class from the moment it was built until after it has been renovated. The share of heating carriers, however, was allowed to change regardless of such renovations.

Four scenarios were developed, “Base” a base case scenario based on observed trends, “Thermal” a scenario achieving wide diffusion of thermal carriers, “Heat Pump” a scenario achieving a widespread use of heat pumps, and “+Conservation” a scenario combining a large extent of energy efficiency measures with the assumptions in the other scenarios.

When applying their scenarios Sartori et al. took into consideration the fact that habits need time to change and that there might be necessary to set up an infrastructure, by using a transition period from 2010 to 2020 for new and renovated buildings. In addition a part of the stock was gradually converted to new heating carriers share.

Both the total energy demand and the electricity consumption were assessed in the study. The “Thermal” scenario had the largest total energy demand, although the share of electricity was lowest in this scenario. For the “Heat Pump”- scenario the opposite was observed, the total energy demand decreased with 2 TWh/year, but the share of electricity was 85%. Consistent in all scenarios with conservation measures the electricity demand was lower than in the reference year 2005, with a reduction varying between -8 and -16 TWh/year. Even if the effect of thermal carriers ranged between -6 and +12 TWh/year the increase never counterbalance the reduction in electricity demand. Further, according to the results large scale conservation measures will allow reducing both the electricity and the total energy demand from present day level while the building stock grows.

(Sartori et al., 2009)

2.6 Energy assessment models

The different studies, as presented in the preceding chapters, all base the energy balance calculation for buildings on slightly different methodologies. The approach relevant for the current work is briefly introduced in this section. The interested reader is referred to the sources for an in depth understanding of all parameters and assumptions.

2.6.1 Material Flow Analysis

A Material Flow Analysis (MFA) is described as a systematic assessment of the flows and stocks of materials within a system defined in space and time. “It connects the sources, the pathways, and the intermediate and final sinks of a material.”(Brunner and Rechberger, 2003). The law of the conservation of mass ensures that the results of a MFA can be controlled by a material balance comparing all inputs, stocks, and outputs of a process. It delivers a complete and consistent set of information about all flows and stocks of a particular material within the defined system (Brunner and Rechberger, 2003).

2.6.2 TABULA and EPISCOPE

The Intelligent Energy Europe Project TABULA (Typology Approach for Building Stock Energy Assessment), evaluated the building typologies being used in European countries and based on these developed a common concept. The result of this effort was a creation of national residential building typologies in 13 European countries (TABULA, 2012). When considering building characteristics there are large differences in the dwelling stock, both within each country and across nations. The TABULA project aimed at laying a basis for models of the building stock, by handling this variety and providing a public data source on the building sector. This was achieved by dividing the dwelling stock in different categories and classifying the national building stocks with information on typical building characteristics, both with regard to the thermal quality of the building envelope and the energy systems in use (Loga and Diefenbach, 2013).

The EPISCOPE project (Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks) is a continuation of the TABULA work. It is an ongoing project lasting from April 2013 to March 2016. The strategic objective has been described as “to make the energy refurbishment processes in the European housing sector more transparent and effective.” The conceptual framework is based on the national residential typologies developed during the TABULA project and the main activity is “to track the energy refurbishment progress of housing stock entireties of different scales.” In addition “the implementation rate of different refurbishment measures will be determined and compared with those activities which are necessary to attain the relevant

climate protection targets”. It is also “intended to track the actual measured consumption after refurbishment as far as possible to verify the targeted savings”. (EPISCOPE, 2013)

The project will complement TABULA with typology schemes from 6 additional countries, and national interpretations of new buildings and Nearly Zero Energy Buildings shall be included. The EPISCOPE pilot actions are done on three levels, national building stock, regional building stock and municipalities or housing companies. There are 7 countries contributing to the national building stock level, Austria, England, Germany, Greece, Netherlands, Slovenia and Norway. On the regional building stock level two countries are in the pilot project, Italy and Spain. At the last level five countries are contributing, Hungary, Ireland, Denmark, Belgium, Czech Republic, Cyprus and France. In Norway the Norwegian University of Science and Technology, NTNU, is involved with the project.

(EPISCOPE, 2013)

The conceptual framework of the EPISCOPE project will be based on building typologies developed during the TABULA project (Loga & Villatoro 2013). A brief introduction of the TABULA method is thus in its place.

The method developed in the TABULA project consists of

- A harmonized data structure which is the foundation of a building data base;
- A standard reference calculation procedure for determining the heat need and the delivered energy demand;
- A scheme for assessing the calculated energy wares in terms of primary energy, carbon dioxide emissions and heating costs;
- A scheme for adapting the calculated energy use to the level of energy consumption which is typical for the respective building types and energy performance levels of the different countries;

(Loga & Villatoro 2013)

The method focuses on the energy use for space heating and domestic hot water of residential buildings, while cooling, air conditioning, lighting and electrical appliances have been left out. As TABULA aims to show the relevant parameters determining the energy consumption of a building in a realistic way yet at the same time keeping the method as simple as possible, averages are used when applicable.

The energy needed for space heating is calculated by applying the seasonal method according to EN ISO 13790 on the basis of a one-zone model. The external boundary conditions are defined for each country for a standard base temperature. In the case of significant climatic differences between regions of a country as for Norway, several climate datasets are supposed to be provided. For the utilization conditions as room temperature, air exchange rate etc. standard values are used. The envelope area is calculated based on the buildings external dimensions as established in the Intelligent Energy Europe project DATAMINE.

(Loga and Diefenbach, 2013).

2.7 Occupancy behavior

NVE defined behavior as *“the conscious and unconscious choices that consumers make within defined frameworks such as legislation, regulations, provisions and what is available on the market”*. (NVE, 2013)

Different occupants lead to different energy use in otherwise equal houses as comfort and security play an important role in energy consumption. Some people may feel safer with the light on during night, some have an extensive amount of electrical appliances and others may require a high indoor temperature. Thus, the energy consumption in two identical houses can be very different, depending on the number of people living there and their energy-related behavior (NVE, 2013).

According to NVE behavior is determined by two factors, extrinsic and intrinsic motivation. Extrinsic motivation is when an activity is motivated by the potential of achieving a reward or reaching a goal beyond the activity itself. Intrinsic motivation is when the activity is carried out for the enjoyment of the activity itself. (NVE, 2013)

Acceptance from the surrounding environment is pointed out as an important example of intrinsic motivation, as well as the desire to increase ones status. NVE referred to a study with some amusing outcomes from people wanting to seem environmentally aware. Such as homeowners investing in solar panels, but placing them on the side of the house facing the street, regardless of which side that provides the best conditions for electricity production. (NVE, 2013)

Economic benefits are found to be important drivers for energy behavior, both with regard to investments in new energy-consuming equipment and in daily use of the equipment. Furthermore, in general households require a short payback time for their investments. In addition they tend to think carefully about the investments they make, but less about daily consumption. Thus households attribute a much higher value to investment costs than to operating costs, an obstacle to many efficiency measures which households could have implemented if a longer pay-back time was acceptable. (NVE, 2013)

Risholt and Berker found, unlike other studies, that the homeowners interviewed were very conscious about their own energy use. All eleven informants implied that they only used the amount of energy necessary to reach an appropriate comfort level, although the description of “appropriate level” varied significantly. (Risholt and Berker, 2013)

Peoples practice in their everyday life was found to influence the energy use especially when it came to indoor temperature. Some were willing to live with a lower indoor temperature. Others wanted the bedrooms to be cold, thereby keeping the windows open, and the rest of the house to be very warm, requiring much heating. (Risholt and Berker, 2013)

When reviewing what initiates renovation activities the overall common feature was that renovations were done when necessary. Mostly “necessary” was assessed as when a component reach its end of life. However, the definition of “end of life” for an element varied greatly among the participants. A punctured window was by some a broken one, while others would only change it when it was no longer unavoidable. Furthermore the threshold to initiate work on the house when the homeowners could do it themselves was lower compared to when professional help was needed. (Risholt and Berker, 2013)

According to Blight and Coley other studies indicate that as the buildings become more energy efficient, the occupancy behavior play an increasingly important role in consumption. One of the studies referred found that the contribution of energy behaviors accounted for 51% of the variance in heating energy use when evaluating UK Eco-Homes. (Blight and Coley, 2013)

Blight and Coley performed a sensitivity analysis on the effect of occupancy behavior on passive house dwellings. Realistic, quasi-empirical profiles for different occupancies, lighting and appliance-use were applied to a set of 100 terraced Passive House units, and modelled in a building simulation program. (Blight and Coley, 2013)

In contradiction to the studies referred by Blight and Coley, they found occupancy patterns to be less significant factors. In fact, set-point temperature was found to have the largest impact on annual heating energy use. In a regression analysis performed, set-point temperature, appliance use and airflow behavior were shown to be major factors of total heating energy, while occupancy patterns were shown to have less significance.

(Blight and Coley, 2013)

2.8 Energy saving rehabilitation methods

As illustrated by the Kyoto Pyramid, Figure 3, energy savings in buildings should first and foremost focus on reducing the heat loss through the thermal envelope and the ventilation system. This chapter gives a brief introduction to common ventilation systems along with methods for adding extra insulation to reduce the heat loss.

2.8.1 Measures to rehabilitate the building envelope

A buildings energy balance is mainly influenced by heat transmission through the envelope due to colder outdoor temperature, heat transmission through the ventilation system as well as infiltration and heat gain by internal sources and solar radiation. The building envelope is complex and additional insulation may not always induce the expected savings and may sometimes cause unexpected problems (Novakovic et al., 2007).

When considering the heat transmission through a building's envelope several concepts need to be understood; U-values, thermal bridges and air leakages. The U-value indicates the construction elements insulating capacity. It is defined as the heat flow density through the construction element given stationary conditions and 1 K temperature difference between indoor and outdoor temperature. The concept of thermal bridges is closely related to the U-value concept. If a specific part of the construction element has a substantially higher U-value compared to the surrounding construction it is defined as a thermal bridge. It is characterized by the additional heat loss of this particular area. In addition air leakages will occur in a buildings envelope increasing the heat loss furthermore. These concepts are thoroughly explained by (Novakovic et al., 2007) and the interested reader is hence referred to this source. In the following section some aspects of rehabilitation of buildings by applying additional insulation are provided.

It's rarely economically feasible to add insulation to buildings unless other measures are applied as well. Insulation applied on the outside of the already existing construction is the best way to minimize heat losses through the wall. The insulation is applied as a plate or a mat of mineral wool, giving the wall a coherent insulation layer for the entire length of the wall. Furthermore, it's of crucial importance to minimize air leakages which often appear in the transition between the walls and the roof or floor. When applying more insulation the natural air leakage will be reduced and more ventilation may be required to maintain the indoor air quality.(Byggforsk, 2004c)

According to the diploma of Olav Aga, when insulating a wall the existing cladding, barge and the wind sheeting are removed, the wall extended and the insulation applied, before new wind sheet and cladding is applied(Aga, 2013).

Additional insulation can be applied on floors facing unheated cellars, either on warm or cold side. However, according to Byggforsk additional insulation of such floors have little impact on the total heat transmission of the building, and can even lead to moisture damage (Byggforsk, 2004a). By insulating the floor the temperature in the cellar will be reduced for large parts of the year inducing a higher relative humidity. Applying the insulation on the cold side will reduce the risk of moisture damage, and is therefore recommended. (Byggforsk, 2004b)

Whenever the ceiling is facing a cold unheated attic the insulation can be applied on the attics floor. Problems with moisture can also occur when insulating roofs, as described for floors, and thus increased ventilation may be needed (Byggforsk, 2005).

2.8.2 Principles and systems for ventilation of dwellings

For dwellings built before the 1970'ies natural ventilation is the dominant type. The air is supplied to the building from valves in walls and windows as well as general infiltration, and exhausted through ducts from bathrooms and the kitchen. The driving force is the pressure difference between the building and its surroundings. Mechanical ventilation only differ from natural ventilation because the exhaust is driven by an exhaust fan installed in the exhaust ducts(Byggforsk, 1994a).

Both natural and mechanical ventilation is reasonably cheap to install and require little maintenance, however neither will provide reliable ventilation and the heat loss related to the ventilation is large. As the building regulations require tighter building envelopes reducing the infiltration to a minimum, better ventilation of the building is essential both to obtain a good indoor air quality and to keep the moisture related problems to a minimum.

Balanced ventilation provides the building with the required air flow through ducts and valves and the heat loss through the ventilation is kept at a minimum with a heat exchanger, where heat in the exhaust air is exchanged with the fresh supply air. (Byggforsk, 1994b)

2.9 Green House Gas emissions

2.9.1 Introduction of the concept

The greenhouse effect is what keeps the earth inhabitable and greenhouse gases are thus vital to the survival of all species. However, since the industrial revolution however the increasing use of fossil fuels has led to an enhanced greenhouse effect increasing the temperature on earth. (Houghton, 2009)

The most important greenhouse gas (GHG) increasing in the atmosphere as a result of human activities is CO₂. Human activities are estimated to have increased the atmospheric CO₂ concentration with 36% since 1700. This is often the gas most people associate with the greenhouse effect. However, other gases are important as well, such as methane and nitrous oxide. (Houghton, 2009)

In addition to the contribution of GHG's land use change resulting from human activities also contribute to the increased greenhouse effect (Houghton, 2009). Global warming is thus a complex concept, and an in depth analysis of all factors contributing to the increased global temperature is beyond the scope of the current work. A complete and thorough briefing is provided by (Houghton, 2009)

Assessing the GHG emissions from different energy sources require a common definition across both energy carriers and national borders. The common way of calculating the emissions resulting from energy use is by multiplying the emission intensities of each energy carrier with the amount of energy covered by said carrier.

The debate also encompasses the intensity that should be attributed to each energy source. For instance, many argue that Norwegian hydropower is a clean energy source, i.e. is related with no emissions. While the production of the hydropower itself may be emission free (information from (Hertwich, 2013) suggest otherwise), building the plant is not. Thus the total production in a life cycle perspective is subjected to emissions and the hydropower should be attributed with emission intensity. In addition Norway is part of the Nordic Power Market which in turn is connected to the European Power market through transmission lines to Germany and the Netherlands (Olje- og energidepartementet, 2013). The electricity used in Norwegian homes are thus not entirely based on hydropower and the emission intensity for the Norwegian electricity mix is somewhat higher compared to the one related to hydro power production.

The increased focus on renewable energy sources has also lead to a strong debate on how to assess the emission intensity of bioenergy. The traditional practice in life cycle assessment of bioenergy has been to assume that any CO₂ emission related to the biomass combustion equals the amount of CO₂ absorbed in the biomass. Therefore the assumption has been that

biomass combustion is neutral, inducing no climate change impacts. However recent studies have altered this interpretation. Even if the CO₂ released by biomass combustion will be captured by biomass regrowth the CO₂ will spend time in the atmosphere before being captured and thus will induce a climate change impact (van Zelm et al., 2014). Additionally chopping down a tree does not automatically ensure that a new tree is grown, and regrowth takes much longer than chopping the tree down in the first place. Therefore emission intensities are attributed both to biomass energy and Norwegian electricity production. The emission intensities used for the current work is introduced in chapter 3.5.3.

2.9.2 Literature review

While the total energy consumption in Norwegian buildings increased by 33% from 1990 to 2010, the Green House Gas emissions were decreased by approximately 30%. This is because the amount of petroleum products used for space heating has decreased significantly over the years, mainly substituted by electricity and to some extent biomass and district heating (Bøeng and Holstad, 2013). However it should be mentioned that the biogenic emissions resulting from biomass combustion, are rarely taken into account and electricity production is often assumed to be emission free, when calculating these numbers.

Buildings only contributed to 3% of the national emissions in 2007. According to the projections from Perspektivmeldinga the emissions originating from buildings will be 2.3 Mt CO₂-eq in 2020 (biogenic emissions not accounted for). Nevertheless compared to the reduction target of 12 Mt CO₂-eq set by Klimakur, buildings have a significant potential for emission reductions (NVE, 2010).

Sandberg and Brattebø evaluated the future GHG emissions and three alternatives were established. Alternative A, assuming Norwegian electricity mix for all electricity consumption, alternative B, assuming the Nordic electricity mix, and alternative C, assuming all electricity consumption, which extends the current demand level, is based on imported electricity from marginal generation technologies changing over time, based on information from (Graabak and Feilberg, 2011).

The results for both alternative A and B showed that the overall GHG emissions remained quite stable during 2000 – 2050. Alternative C showed a rapid increase of emissions stabilizing on a level 62% higher than the 2000 level in year 2050. Furthermore, significant overall emission reduction in the dwelling system, towards 2050 was assessed as difficult to achieve. Although the results were not directly comparable to other studies, due to differences in system definitions, these results were found to be in striking contrast to other studies. The future energy demand and GHG emissions found in other studies were likely to be underestimated. The authors also highlighted the particular challenge of the Norwegian dwelling stock. As more than 90% of the direct energy consumption already is covered by energy carriers with low GHG emissions, i.e. hydropower based electricity and biomass,

further reductions are challenging. In a global perspective however, less energy consumption in Norwegian dwellings would free more electricity, which could substitute fossil sources in Europe. (Sandberg and Brattebø, 2012)

Pauliuk et al. investigated which combinations of building codes, lifestyle changes and energy savings for hot water, lighting and appliances that may reduce the carbon footprint of the Norwegian dwelling stock, by at least 50 % by 2050. The results showed that the sectorial emissions may drop 30 – 40 % during 2000 – 2050, for scenarios where the stock is completely transformed by either renovation or construction to the passive house standard. Renovations, having a lower upstream impact, will lead to lower carbon footprint than reconstruction. However, the results also showed that full transformation will not be sufficient to achieve an emissions reduction of 50% or more, which is required to limit global warming to 2 degrees. (Pauliuk et al., 2013)

NVE studied emission reducing measures for buildings in Norway by analyzing measures to reduce the use of fossil energy in the buildings use phase. The buildings life cycle including the emissions related to its construction and demolition were thus not included in the analysis. The emissions from Norwegian buildings were assumed to decrease from 1.6 Mt CO₂-eq in 2007 to 1.3 Mt CO₂-eq in 2020, which will amount to approximately 2% of national emissions in 2020. Dwellings were assumed to emit 0.63 Mt CO₂-eq in 2020 due to 1.8 TWh consumption of fossil energy. No emission intensity was attributed to electricity in this study. (NVE, 2010)

Dokka et al. performed an analysis with the aim of calculating the energy use, embodied emissions and the total CO₂ emissions for a typical residential building. Four different levels of Zero Emission Buildings were described. ZEB-O + EQ take into account the emissions related to all energy use except the energy use for appliances. ZEB-O accounts for all emissions related to operational energy use included the energy use for equipment. ZEB-OM takes into account all emissions related to operational energy use as well as the embodied emissions from materials and installations. ZEB-COM takes into account the same as ZEB-OM as well as including emissions related to the construction process of the building. The goal was to achieve the level ZEB-OM. (Dokka et al., 2013)

The results found by Dokka et al. showed that it was rather easy to achieve a ZEB-O level building, where the energy demand during the year is equaled by the electricity production, on site by PV-panels. This would ensure both a Zero Energy Building as well as a Zero Emission Building, if only the emissions related to the operation of the building are taken into account. It was more difficult to achieve the level ZEB-OM. The production from the PV-panels only covered 77% of the emissions from operation and materials. Another important results from this analysis was that the preliminary results indicated that the embodied emissions are significantly higher than those related to operational energy use. (Dokka et al., 2013)

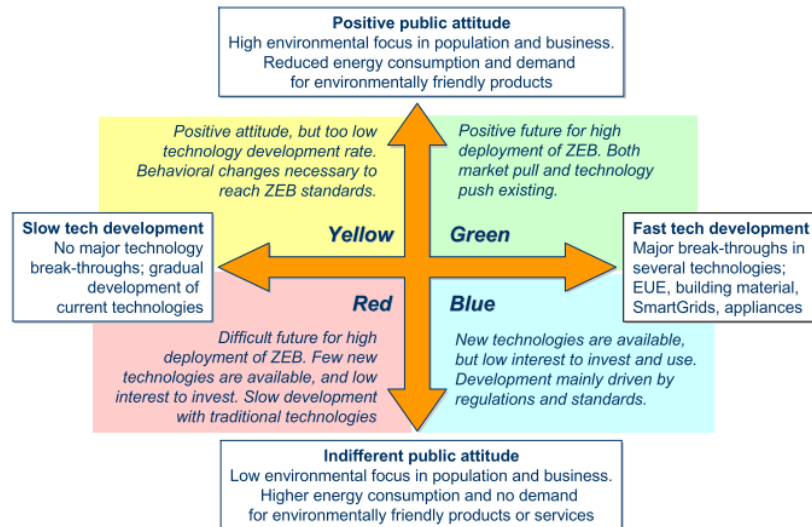


Figure 7: ZEB-storylines (Graabak and Feilberg, 2011)

Graabak and Feilberg studied possible future emission scenarios based on the electricity demand and production in Europe with a time perspective going to 2050. The study was based on a storyline methodology characterized as a “what if a certain development occurs”-analysis rather than an analysis seeking the optimal solution. The most important factors representing large uncertainties for the implementation of Zero Emission Buildings were identified as the technological development and the public attitude. (Graabak and Feilberg, 2011)

During the study four storylines were developed; Yellow, Green, Blue and Red. These storylines were established as a table of quadrants divided by four points, Positive public attitude, Fast technological development, Indifferent public attitude and Slow technological development, all representing on side of a cross-sectional divided table, as seen in Figure 7. The specifications given for each storyline is not a forecast of an optimal future, but the project’s assumption of possible futures. The Red storyline is given by the combination of slow technological development and indifferent public attitude. The Yellow storyline is described by a combination of slow technological development and positive public attitude. The Blue storyline is the combination of indifferent public attitude and fast technological development and the Green Storyline of both positive public attitude and fast technological development. Within each storyline different scenarios can be established and analyzed. An optimal solution was sought within each storyline but no optimization between the different storylines was sought. (Graabak and Feilberg, 2011)

Table 4: Development of specific CO₂-emissions for all scenarios [gCO₂/kWh] (Graabak and Feilberg, 2011)

	2010	2030	2040	2050
Red	361	284	271	258
Yellow	361	233	211	192
Green⁷	361	223	187	157
Ultra Green	361	196	113	31
Blue	361	183	136	114

Based on the storylines and literature sources Graabak and Feilberg gave scenarios on the development of the electricity demand in Europe following each of the storylines. Along with fuel prices, emission quota prices and emission factors the development in the European electricity production mix was established for each storyline. The marginal emissions in each storyline were calculated and are displayed in Table 4.

The marginal emissions were calculated as the marginal change in emissions in Europe as a consequence of changes in the demand of 1 TWh in Norway. Through transmission lines Norway is connected to other countries, and an increase in demand in Norway will in most cases increase the production in other countries.

In addition to the four scenarios given Graabak and Feilberg ran a fifth scenario constructed to provide knowledge about a nearly emission free electricity production. The scenario, termed Ultra Green was only considered in a long term scenario towards 2050, and the numbers given for this scenario for the years 2030 and 2040 are therefore extrapolations based on numbers for 2010 and 2050 rather than calculations.(Graabak and Feilberg, 2011)

⁷ Although one may expect the Green scenario to give lower CO₂ emissions compared to the Blue scenario this is as given by Graabak and Feilberg. This is explained by a very high renewable production in the Blue scenario. For further information see Graabak and Feilberg 2011.

2.10 Economics

This chapter provides a brief overview of studies examining the economics of buildings, as well as an introduction to Life Cycle Costing.

A study by Brown et al. assessed renovation packages for increased energy efficiency for multi-family buildings in Sweden. The method included calculation of bought energy demand, a life cycle cost analysis and assessment of the buildings according to the Swedish environmental rating tool Miljöbyggnad (MB). Three buildings, a terrace of five row-houses built in 1973, an apartment building from 1973 and an apartment building from 1963 were considered in this study. For each building three cases were established, a base case and two different packages. The base case was established as the minimum level of investment required to maintain the present function of the building with the present bought energy demand. The first of the packages included measures with moderate efficiency increase, where a moderate decrease in bought energy was aimed for, while the second included measures with large efficiency increase, where a large decrease in bought energy was aimed for.

In each case the packages and the base cases were compared economically using an LCC with a net present cost method over a 50 year period. In the calculations a general rate of inflation of 1.2% and a discount rate of 5% was utilized. The costs included in the analysis was the investment costs in year 1 required to establish the given function as well as the operation and maintenance costs required to maintain that function over the given period-of-analysis. As many of the measures applied included systems with shorter technical lifetime than 50 years discounted re-investment costs for these systems were included. However, no end-of-life cost was included, as the buildings were not assumed to have reached their end-of-life after 50 years. The results from this analysis showed that the high efficiency packages reduce the energy use by up to 50% for all cases. For all buildings the LCC showed that the higher efficiency package also resulted in a higher LCC, although the increase in LCC is significantly smaller percentagewise than the decrease in energy use.

(Brown et al., 2013)

In 2010 Multiconsult, commissioned by Norwegian District Heating, investigated the costs of conversion from a direct electric space heating system to a waterborne one. Based on information from SSB they found that the cost of these installations had increased significantly since 2003 and that the cost of materials associated with the installations had increased the most. Based on information provided by Prognosesenteret it was found that the prices are higher in Norway compared to Sweden, and that the prices differ significantly across the country. Multiconsult found there to be large insecurities regarding the numbers and which cost elements are included in the pricing. The results from this investigation revealed variations in the costs between 270 – 777 kr/m², both based on experience as well as other analyses. The cost of upgrading to a waterborne system was found to be 5 – 10% higher

than if a waterborne system is implemented during construction. The current knowledge and experience when it comes to implementing such systems in existing buildings were found to be poor, and more focus on cost efficient solutions were needed. (Multiconsult, 2010)

Commissioned by the former ministry of municipalities Asplan Viak performed an extensive study of component requirements regarding energy rehabilitation of buildings. The scope of the study was to investigate and outline possibilities for stating minimum standards and requirements for the energy performance of building components.

The cost efficiency of different energy rehabilitations was also considered. Replacement of windows, for instance, was found to be cost effective with as low a U-value as $0.8 \text{ W/m}^2\text{K}$, while energy efficiency requirements for renovation of outer walls and roofs were not cost effective at a level equal TEK 10. Including LCA for the components was discussed early in the investigation. However, the conclusion was that there currently exists too little knowledge for such an evaluation and therefore only Cost-Benefit Assessment was used for the component requirements.

As stated by the authors some of the energy saving potential in the building sector could be achieved by ambitious energy requirements when large rehabilitations are to be implemented. However, this could make it less interesting to rehabilitate at all, therefore they conclude that it's better to introduce component requirements, forcing the consumers to use energy efficient components when they renovate. This will ensure a gradual upgrading of the building stock. Better financial support systems were called upon to initiate energy efficient renovation.

(Asplan Viak, 2012)

The Socio Economic Manual prepared by NVE states that the calculation rent when considering extensive projects should be calculated from case to case, while for smaller projects should be based on the pre-defined rents, according to risk classification. Such rents are at 4%, 6% or 8%, based on a risk free rent of 3,5% and an additional risk related rent of 0.5, 2.5 or 4.5 %. For energy economizing measures the standardized rent according to NVE is 6% - 8% for measures invoked by the end user. If the measure has a clear environmental benefit 6% is recommended, while 8% is recommended in all other cases. (Jensen et al., 2003)

2.10.1 Life Cycle Costs

Definition from Stanford of LCCA (Life Cycle Cost Analysis): *“LCCA is a process of evaluating the economic performance of a building over its entire life. LCCA balances initial monetary investment with the long-term expenses of owning and operating the building.”*(Stanford University, 2005)

Energy efficiency projects are often found not only to be environmentally beneficial, as they reduce the GHG emissions, but also in many cases an economically viable option. However, energy efficiency projects are regarded as too pricy because the investment cost is given too much significance. Forte describes this as the “iceberg phenomenon” as depicted in Figure 8, where the consumer only has a clear view of the tip of the iceberg, i.e. the investment costs. An investment does, however, often involve other costs beyond the mere investment. According to Forte the investment costs of a product consuming energy and requiring maintenance only represents 25% of the total picture, and a common misconception is that both parts of the iceberg are proportional in size. This will lead to poor investments, both with regard to the environment and the economy of the investor. Life Cycle Costing is described as *“a generic method that enables comparative cost assessments over a period of several years”*. (Forte, 2012)

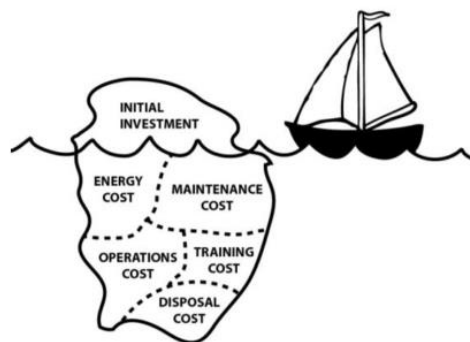


Figure 8: The Iceberg metaphor by (Forte, 2012)

An LCC can be carried out for two main reasons, either to determine accurate financial forecasts or comprehensive cost estimates for accounting purposes, or to facilitate a particular decision. In the first case an accounting model, including all possible cost factors contributing to the total economic impact of the project under consideration, is needed. In the second case considering all cost factors are not necessary, only those that differ between the alternatives under consideration need to be included. In the energy efficiency context of the current study such alternatives can be different rehabilitation measures applied to an existing house. Often one of the alternatives is to do nothing, referred to as “the base case scenario”. After such alternatives are described the single criterion allowing identification of the best option has to be established. The most common criteria, as explained by Forte, are “minimum total cost” or “maximum profit”. (Forte, 2012)

When considering an investment over time defining the time horizon itself, is of major importance. The same horizon has to be used for each of the alternatives and is restricted by the longest physical lifetime amongst the alternatives, as well as the investment horizon of the decision maker. The time horizon will also be shorter than the functional lifetime, defined as the total time period the functional need exists for which the product is used. (Forte, 2012)

2.10.2 Systems of funding

In order to increase the public will to implement energy efficient measures different funding schemes are available. Enova, for instance, has many measures of funding relevant for rehabilitation of existing single-family dwellings. Up to 5000 NOK can be given in funding for using a qualified energy consultant who provides the owner with a plan of energy efficient measures for the dwelling along with an energy label (Enova, 2014b). If the owner wish to implement these energy efficient measures, funding schemes are available for that as well. Four different energy efficiency measures are given different funding. These are replacing an oil boiler, changing the heating system from direct electric heating to water-borne renewable heating, establishing a solar collector system and establishing a central heat management system. The amount of funding range from 20 – 35 % of the total cost, dependent on the measure in question(Enova, 2014c).

Switching from direct electricity to a renewable energy source combined with waterborne space heating, is another one of Enova's funding systems. If the dwelling already has a waterborne space heating distribution, funding amounting to 10% of the total investment for the renewable energy source, such as heat pump or pellets boiler will be given. The upper limit is 10 000 NOK. Whenever a waterborne space heating distribution is needed, the funding amount to 20% of the total investment cost of both the energy source and the heat distribution system. The upper limit for such cases is 20 000 (Enova, 2014c).

Enova also provides funding for energy related rehabilitation measures carried out in dwellings. This funding scheme has two levels. Level 1 is set to 700 kr/m² and a maximum of 125 000 kr. Level 2 is set to 600 kr/m² and a maximum of 110 000 kr. The funding has three requirements. First, the heat transmission through the building envelope and the ventilation system must at least be reduced by 30% and be less than some minimum requirements. Second, the net energy demand must be reduced to a minimum level, and third the heating system cannot be based only on direct electricity or fossil fuels. Level 1 has stricter requirements compared to level 2 and thus gives a higher amount of funding (Enova, 2014d).

In addition to the national funding schemes provided by Enova some of the municipalities offer different fundings for energy rehabilitation measures. For instance, the municipality of Oslo where funding is given both for additional insulation, heat pumps and heat recovery of ventilation air, among other measures (Enøketaten, 2013).

3 Methodology

The current work comprises three different analyses, of which the methods and assumptions are presented in this chapter. As the current work is based on the MSc project work carried out during the fall of 2013 the first section provides a brief overview of the method and results. Afterwards follows the methods and assumptions of the three analyses carried out in the current work, as well as a description of the energy rehabilitation packages chosen to evaluate.

3.1 The MSc Project work

During the MSc Project work carried out during the fall of 2013 an energy balance model used to calculate the energy balance of typical Norwegian Single-Family dwellings were developed (Storvolleng, 2013). This chapter will give an introduction of the model used in the MSc Project work, along with a summary of the most important findings.

3.1.1 Assumptions for the Norwegian dwelling stock

The Norwegian dwelling stock was divided in three main dwelling types as well as six age cohorts, depending on the year the dwelling was ready for use. The input data for the model was to a large extent based on a study performed by Enova, aiming at revealing the potential and the barriers of energy savings in the Norwegian dwelling stock (Mjønes et al., 2012). The dwelling types and age cohorts were chosen in accordance with this study and are as follows:

Dwelling types

- Single – Family dwellings
- Divided small houses, including terraced houses and multi-family houses divided vertically or horizontally
- Apartment blocks

Age cohorts for:

- Dwellings built before 1956
- Dwellings built during 1956-1970
- Dwellings built during 1971-1980
- Dwellings built during 1981-1990
- Dwellings built during 1991-2000
- Dwellings built during 2000-2010

(Mjønes et al., 2012)

This specific classification of the Norwegian dwelling stock is based on the different age cohorts' respective building traditions as well as the technical characteristics for buildings within these time periods. The dwellings has been classified as such based on their differences considering size, design and living patterns (Mjønes et al., 2012).

The MSc project work focused on one building type and three age cohorts, as there are other theses handling the rest of the dwelling stock. The building type in focus was single-family dwellings, and the age cohorts are the three first ones, “before 1956”, “1956-1970” and “1971-1980”.

3.1.2 The Norwegian single-family dwelling

Table 5: The distribution of Single-Family dwellings (Mjønes et al., 2012)

The distribution of Single – Family dwellings in 2010 based on year of construction					
	Total area lived in	% - of area lived in	No. of households	% - of households	Average BRA per household
SFH	169005646	100%	1080955	100%	156
> 1956	39804369	24%	272651	25%	146
1956 – 1970	31139401	18%	212898	20%	146
1971 – 1980	32201810	19%	212545	20%	152
1981 – 1990	35392847	21%	195910	18%	181
1991 – 2001	17162144	10%	107623	10%	159
2001 – 2010	13305075	8%	79367	7%	168

Single-family houses were defined by Enova to be a collective term for both the normal single-family house, located in every town, as well as farm houses. It is a detached house normally having two floors, and the main construction material is timber. This dwelling type accounted for 65% of the overall dwelling area in 2011. (Mjønes et al., 2012)

3.1.3 The Energy balance model from the MSc Project work

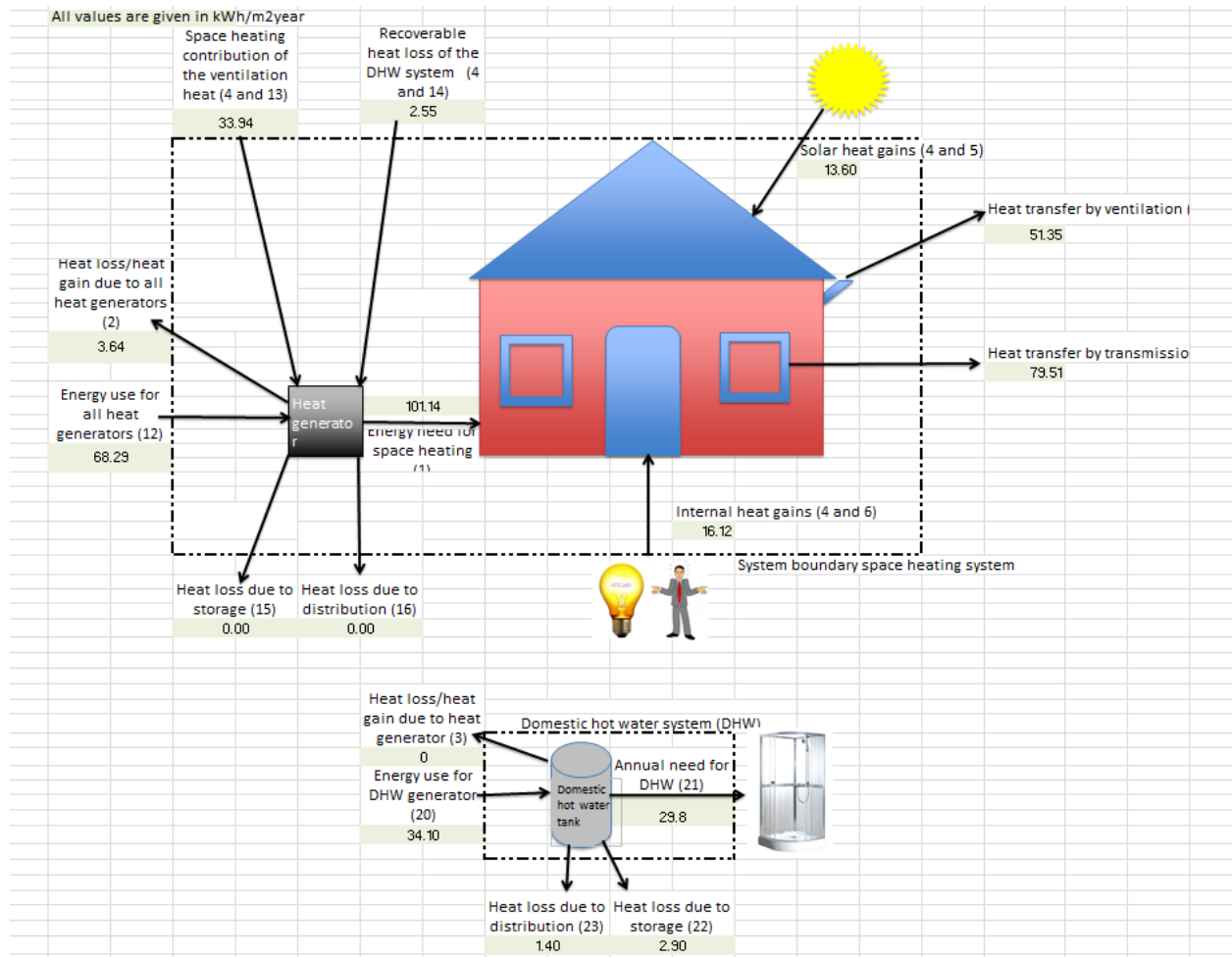


Figure 9: The energy balance used both in the MSc Project work and the current work

An energy balance model was developed based on the equations and information given in the TABULA method (Loga and Diefenbach, 2013). It was based on the methodological framework of MFA, using a well defined system boundary, processes and flows. However the flows were based on energy per floor area and were all expressed as kWh/m², in contrast to the flow of a material, as defined by the MFA methodology (Brunner and Rechberger, 2003). All the parameters used in the TABULA method are summarized in Appendix B.

As can be seen from Figure 9 two energy balances were carried out, one for the domestic hot water (DHW) system, and one for the building with all heat generation and losses, respectively. These are linked as some of the heat loss from the DHW is recovered as an input to the building. All flows with the corresponding equations are given in Appendix C in addition to all the parameters that had to be based on literary research along with their respective sources. The model only takes into account the energy use for space heating and domestic hot water. Electricity needed for lighting and appliances are not included, only the indirect heat gains from these. In addition no behavioral determinants are taken into account, but the vintage as well as the thermal state of the building envelope are accounted for.

3.1.4 Assumptions for the model

The study performed by Enova defined the standard dwellings in Norway beyond just the type and age cohort. Each building standard was defined with parameters such as area, U-values, temperatures and air change rates. The dwellings were defined for three states, the original building as it was when the first family could move in, a historical upgrading of the buildings envelope and an upgrade to TEK 10 level. The historical upgrading was defined based on both a survey, conversations with building assessors and construction workers, and data sheets from Sintef Byggforsk, and was defined as renovations done either on the entire building or only specific parts (Mjønes et al., 2012). The upgrading to TEK 10 standard was defined as future energy measures that would give the building the requirements of TEK 10, and was described to replace the historical upgrading (Mjønes et al., 2012). During the MSc Project work four technical stages for the building envelope in each age cohort were defined, the original as it was built, the historically upgraded and TEK 10 upgraded as defined by Enova, and rehabilitation to Passive House standard. TEK 10 rehabilitation is defined as a standard rehabilitation since it would take the buildings envelope to the standard corresponding to new buildings today. The Passive House standard rehabilitation was seen as an extensive rehabilitation measure. This is in accordance with the TABULA methodology described in chapter 2.6.2. All the assumptions for the energy balance carried out in the MSc Project are summarized in Appendix D.

Based on the information provided by Enova along with the mentioned assumptions four different technical packages for each building cohort were established; the original building as it was constructed, the historical upgraded building as defined by Enova, a TEK 10 rehabilitated building and a Passive House rehabilitated building. For all packages the energy balance for the building was assessed.

3.1.5 The results from the MSc Project work

This chapter provides a brief summary of the most important findings from the MSc Project work. For a more extensive outline of these results see Appendix D.

The net energy demand for space heating was mainly influenced by two flows, the heat transmission through the thermal envelope and the ventilation heat losses. With the aim of reducing the energy demand in buildings, reducing the heat loss through the thermal envelope should be the main priority. For old and poorly insulated buildings the roof and walls were found to be the most critical to rehabilitate. In addition the results showed that changing the windows would induce a large reduction of the total heat transmission compared to the relative size of the window area.

Rehabilitating this part of the dwelling stock had an energy saving potential of 6.95 TWh/year if rehabilitated from historical rehabilitation to TEK 10 standard. If the dwellings were rehabilitated to Passive House level the energy saving potential would be 9.83 TWh. These numbers were both for rehabilitation without mechanical ventilation with heat recovery. The results showed that the buildings could not achieve TEK 10 or Passive House energy requirements without heat recovery of the ventilation air. In addition the energy supply system for the dwellings have to be changed to meet the requirement of energy carriers in the TEK 10 and Passive House standards. If heat recovery of ventilation air and Heat Pumps were part of the rehabilitation packages the energy saving potential was assumed to significantly increase.

During the MSc Project work the energy balance model was assessed and the uncertainties of the model were thoroughly discussed. Since the current calculations are based on the same model many of the uncertainties portrayed in the Project work will influence the calculations in this work as well. The following section gives a summary of these uncertainties:

- Windows: The U-value for windows used in the oldest age cohort was probably underestimated by Enova. Therefore the net energy demand for the original building envelope may be underestimated.
- The chosen space heating system is well described by literature and was thus assessed as a robust choice (Appendix D). However, the system efficiencies and thus the losses were found based on numbers provided by the TABULA method. Therefore these numbers may not be representative for the Norwegian systems.
- Thermal bridges were not considered and the bridge factor thus set to the standard values with no regard to whether or not this was a valid assumption. This may significantly have influenced the results of the rehabilitated envelopes.
- The indoor temperature was not increased when further insulation was applied even though literature suggests that the indoor temperature is increased due to better thermal envelopes (Hille et al., 2011).
- Air change rates were not increased when more insulation were applied. This should probably have been done as further insulation decrease the air infiltration. Hence more air is needed to maintain the indoor air quality.
- Climate zones were found to influence the results, deviating greatly over the different regions. As most sources use the Oslo climate and standard values are based on this climate it was assessed as the best one. In addition it represents the area with the largest density of dwellings and would thus yield good results when looking at the entire building stock.
- Considering that the model used for the calculations were based on the TABULA methodology which isn't developed with special regards to Norwegian conditions the results may not be representative for Norway. However, the results were compared to other Norwegian and Swedish studies and the TABULA method was assessed as satisfactory.

3.2 The energy balance model for the MSc Thesis

The energy balance model used for the calculations carried out in the current work, is very much the same as the model developed during the MSc Project work. Some alterations had to be made, however, as this model calculates the energy demand for a variety of packages, further detailed in the subsequent chapters.

3.2.1 Scope

The scope of the energy balance model is to establish an energy balance for each building taking into account the vintage, climate and possible rehabilitations.

3.2.2 Assumptions and system boundary

Table 6 Distribution of original and renovated state for Single-Family dwellings (Mjones et al., 2012)

	Original state	Renovated	Windows changed	Additional insulation of façade	Additional insulation of roof /floor
Before 1956	9 %	91 %	74 %	64 %	55 %
1956 – 1970	24 %	76 %	64 %	32 %	44 %
1970 – 1980	61 %	39 %	35 %	6 %	20 %

The energy balance is calculated for the model shown in Figure 9 with the given system boundary. Thus, the energy demand considered is the operating energy for space heating and domestic hot water. Embodied energy is not included. System efficiencies of the energy supply system are taken into account.

The energy balance model takes into consideration that the buildings reported by Enova had two technical levels, original and historical rehabilitated building envelope. The report by Enova did also include an overview of the percentage of buildings that were likely to still have the original level, as given in Table 6. As can be seen from this table most of the dwellings from the first two age cohorts can be assumed to have been upgraded, while for the last age cohort most buildings are still at their original state. Therefore when calculating the energy demand for the buildings, to be used in the LCC analysis, the base case will be defined such that buildings from the first two age cohorts are modeled as historically upgraded, while for the last age cohort re at their original state.

The thermal bridging factor will not be varied in the calculations carried out for this MSc Thesis. Following a conversation with Martin Hoberg it was understood that calculating the

thermal bridges in any buildings, and especially in rehabilitation projects is very difficult. Applying more insulation will in most cases reduce the thermal bridges, however to what extent, there is no certain way of knowing. Reaching the thermal bridging factor as given in the requirements of NS 3031 and NS 3037 is almost impossible for smaller buildings, regardless of the construction manner (Hoberg, 2014). Therefore it is assumed that adding more insulation will not ensure that the required bridging factor is reached. The thermal bridging surcharge ΔU_{thr} is therefore held constant at the TABULA classified value “high” of 0.10 [W/(m²K)]. This may not be correct for Norwegian buildings, especially not for the upgraded thermal envelopes, but it has been chosen as such because it is the conservative choice.

The infiltration rate is set to the TABULA standard values “High” for original buildings, “Medium” for TEK 10 rehabilitated buildings and “Low” for Passive House rehabilitated buildings. This reduction of the infiltration rate was only carried out for rehabilitations belonging to case 3, 4 and 5, as these included rehabilitation of the entire building envelope. For rehabilitation package 1 and 2, as the rehabilitations are only carried out on the façade, the infiltration rate is kept as for the original buildings. It should be mentioned that calculating how the infiltration rate changes, with an upgraded thermal envelope is very difficult. However, it is assumed that the infiltration rate will decrease when extra insulation is applied.

The air change rate for the ventilation of the buildings has been changed for this project compared to those set in the MSc Project work.

Based on information from Stene the heat source covering base load is assumed to cover 60% of the power requirements. The Heat Pumps are assumed to cover 80 % of the energy demand, with wood or electricity as peak load(Stene, 1997). The biomass boiler is assumed to cover 90% of the energy demand based on information given by Enova (Enova, 2009).

Further assumptions are given in Appendix E

3.2.3 Outcome

The energy balance provides the results for the net specific energy demand for space heating. A comparison with the standard energy requirements of both the TEK 10 and Passive House standard is carried out to investigate whether or not the rehabilitated buildings reach the standard requirements. In addition the energy balance of the building envelopes close to or achieving the Passive House standard is calculated with a thermal bridging surcharge equal to the standard requirement, to assess how influential this parameter is.

3.3 Rehabilitation packages

A summary of all the rehabilitation packages is given in Appendix F.

This chapter provides an overview of the rehabilitation packages developed for this analysis. The energy balance of each rehabilitation package will be calculated using the energy balance method described in chapter 3.2. The economics of the packages will be investigated using the method presented in chapter 3.4.

According to the literature review a distinction is made between measures reducing the energy demand of the building itself, and those related to the energy supply system (Rambøll AS and Xrgia AS, 2011). The Passive measures are such which reduces the energy demand of the building, usually related to the building envelope, and sometimes the ventilation system is included. In the current work, the passive measures have been defined as only those related to the building envelope. The active measures are those related to the energy supply, in addition to the balanced ventilation system, which has been included in this definition.

When it comes to the energy supply system, none of the packages includes connection to the district heating network. As district heating network is mainly in larger cities, it is chosen to look upon general heating systems which can be applied to all dwellings, regardless of the location. This is also supported by (Sartori et al., 2009) suggesting that district heating will only be used to a marginal extent in the future.

The packages is developed with the aim of providing information about the cost of both implementing only the passive measures, as well as the additional cost of the active measures. Both TEK 10 rehabilitation and Passive House rehabilitation will be examined through these packages. Some packages will include passive rehabilitation of all components, while other only rehabilitate some.

3.3.1 Base Case

This package is designed not to include energy related rehabilitations. The space heating system isn't changed, but the electric panels and the wood stove might need to be changed if they reach their end of life within the period in question. In addition some rehabilitation of the thermal envelope might be needed to keep the envelope at a level where the building is inhabitable. Such rehabilitations are assumed not to influence the energy balance of the building with the exception of window rehabilitations. Following a conversation with Mestervindu the U-value is set to $1.4 \text{ W/m}^2\text{K}$, as this is the highest U-value of their windows (Endal, 2014). It is therefore assumed that when changing windows the worst type on the market is used.

3.3.2 Rehabilitation package 1

Table 7: U-values for rehabilitation package 1

U –values for each building element, based on age cohort and technical level [W/m ² K]						
Building element	TEK 10 standard			Passive House standard		
	>1956	56 – 70	70 – 80	>1956	56 – 70	70 – 80
Walls	0.17	0.18	0.17	0.094	0.097	0.095
Windows	1.2	1.2	1.2	0.7	0.7	0.7
Doors	1.2	1.2	1.2	0.8	0.8	0.8

Rehabilitation package 1 includes component rehabilitation of the facade including the doors and windows. The package includes two levels, where level 1.0 only includes changes to the thermal envelope, while level 1.1 also includes a heat pump to cover base load. This rehabilitation package is carried out with both TEK 10 requirements and Passive House requirements. Therefore the results from this package are both with and without the use of a heat pump in addition to two energy levels regarding the thermal envelope. The subdivision of the package is summarized below.

Further subdivision of the rehabilitation package

- 1.0 Only facade rehabilitation
 - 1.0.1 TEK 10 rehabilitation on all components in question
 - 1.0.2 Passive House rehabilitation on all components in question
- 1.1 Rehabilitation of facade along with installation of an air-to-air heat pump
 - 1.1.1 TEK 10 rehabilitation on all components in question
 - 1.1.2 Passive House rehabilitation on all components in question

3.3.3 Rehabilitation package 2

Table 8: U-values for rehabilitation package 2

U –values for each building element, based on age cohort and technical level [W/m ² K]						
Building element	TEK 10 standard			Passive House standard		
	>1956	56 – 70	70 – 80	>1956	56 – 70	70 – 80
Walls	0.17	0.18	0.17	0.09	0.10	0.09
Windows	1.2	1.2	1.2	0.7	0.7	0.7
Doors	1.2	1.2	1.2	0.8	0.8	0.8
Roof	0.13	0.13	0.13	0.08	0.08	0.08

Rehabilitation package 2 develops package 1 further, including rehabilitation of the roof. As for Package 1 both TEK 10 and Passive House requirements is investigated, and the package is subdivided as shown below.

Further subdivision of the rehabilitation package

- 2.0 Only facade rehabilitation
 - 2.0.1 TEK 10 rehabilitation on all components in question
 - 2.0.2 Passive House rehabilitation on all components in question
- 2.1 Rehabilitation of facade along with installation of an air-to-air heat pump
 - 2.1.1 TEK 10 rehabilitation on all components in question
 - 2.1.2 Passive House rehabilitation on all components in question

3.3.4 Rehabilitation package 3

Table 9: U-values for rehabilitation package 3

U-values based on age cohort [$\text{W/m}^2\text{K}$]			
Building envelope element	TEK 10 standard components		
	>1956	56 – 70	70 – 80
Walls	0.17	0.18	0.17
Windows	1.2	1.2	1.2
Doors	1.2	1.2	1.2
Roof	0.13	0.13	0.13
Floor	0.14	0.14	0.36

Rehabilitation package 3 is a full TEK 10 rehabilitation, including upgrading the entire thermal envelope, installing balanced ventilation with heat recovery and investigation of two different energy systems upgrading, heat pump and biomass boiler combined with electric elements respectively. The package is subdivided into five levels, as given below. The first three sub-packages include installation of a new electric water heater. The two last ones include installation of a water heater that can be used in combination with heat pumps or biomass boiler. This boiler has an electric element which provides the peak load heat.

Further subdivision of the rehabilitation package

All rehabilitation on building envelope elements is to the TEK 10 standard.

- 3.0 Only rehabilitation of building envelope elements.
- 3.1 Rehabilitation on building envelope elements along with installation of balanced ventilation
- 3.2 Rehabilitation of building envelope elements, installation of mechanical ventilation and installation of an air-to-air heat pump for base load, direct electricity and wood fired stoves for peak load.
- 3.3 Rehabilitation of building envelope elements, installation of balanced ventilation and installation of an Air-to-Water Heat Pump for base load combined with an electric boiler for peak load. The package includes installation of waterborne space heating system.

3.4 Rehabilitation of building envelope elements, installation of balanced ventilation and installation of biomass boiler for base load combined with an electric boiler for peak load. The package includes installation of waterborne space heating system.

3.3.5 Rehabilitation package 4

Table 10: U-values for rehabilitation package 4

U-values based on age cohort [$\text{W}/\text{m}^2\text{K}$]			
Building envelope element	Passive House std. components		
	>1956	56 – 70	70 – 80
Walls	0.09	0.10	0.09
Windows	0.7	0.7	0.7
Doors	0.8	0.8	0.8
Roof	0.08	0.08	0.08
Floor	0.08	0.08	0.08

This package is established to investigate the energy demand and costs related to a rehabilitated building with Passive House components. It includes a full rehabilitation of the thermal envelope, except for the last age cohort, where the floor isn't rehabilitated. In addition active measures such as balanced ventilation, heat pump and bio-mass boiler are added to various extents. The first three sub-packages include installation of a new electric water heater. The two last ones include installation of a water heater that can be used in combination with heat pumps or biomass boiler. This boiler has an electric element which provides the peak load heat.

Further subdivision of the rehabilitation package

All rehabilitation on building envelope elements is to the Passive House standard.

4.0 Only rehabilitation of building envelope elements.

4.1 Rehabilitation on building envelope elements along with installation of balanced ventilation

4.2 Rehabilitation of building envelope elements, installation of balanced ventilation and installation of an Air-to-Air Heat Pump for base load and wood fired stoves for peak load.

4.3 Rehabilitation of building envelope elements, installation of balanced ventilation and installation of an Air-to-Water Heat Pump for base load combined with an electric boiler for peak load. The package includes installation of waterborne space heating system.

4.4 Rehabilitation of building envelope elements, installation of balanced ventilation and installation of biomass boiler for base load combined with an electric boiler for peak load. The package includes installation of waterborne space heating system.

3.3.6 Rehabilitation package 5

Table 11: U-values for rehabilitation package 5

U-values based on age cohort [W/m ² K]			
Building envelope element	Passive House std. components		
	>1956	56 – 70	70 – 80
Walls	0.09	0.10	0.09
Windows	0.7	0.7	0.7
Doors	0.8	0.8	0.8
Roof	0.08	0.08	0.08
Floor	0.08	0.08	0.08

Rehabilitation package 5 is established in order to investigate the possibility of rehabilitation towards nearly Zero Energy Buildings.

Further subdivision of the rehabilitation package

5.0 Rehabilitation to Passive House level on all building components, installation of balanced ventilation, installation of an air-to-air heat pump for base load, and wood fired stove for peak load, as well as installation of PV-panels for on-site production of electricity. A new electric DHW-tank is also installed.

5.1 Rehabilitation to Passive House level on all building components, installation of balanced ventilation, installation of an air-to-water heat pump and a waterborne space heating system, as well as installation of PV-panels for on-site production of electricity. A new DHW-tank is installed. This has an electric element covering the peak load heat demand.

3.4 The Economic analysis

This chapter provides the method and assumptions which are used for the economic analysis.

3.4.1 Scope

The scope of the economic analysis is to investigate the financial implications of implementing the rehabilitation packages previously described. The analysis is based upon the economic principles of an LCC as it will balance the investment cost with the long-term expenses of operating the building. The aim of the analysis is to facilitate a decision and will therefore not take into account all costs related to the building over its entire lifetime. This is in accordance with Forte (Forte, 2012). The analyses mainly focus on the costs related to rehabilitations that are relevant for the buildings energy balance.

3.4.2 Economic analysis based on the principles of LCC

The economic analysis rests upon the principles of an LCC, thus this section provides the key factors to consider in an LCC.

The time value of money

As the investment will be carried out in present day, while costs and cost benefits related to the investment will occur in the future, the time value of money is an important term. It reflects why getting 1000 kroner today is better than getting it 5 years from now. As this money can be invested or simply put into the bank, not having them today costs money. Each cost occurring in the future does also have a value today, its Present value (PV), which differs from its Future Value (FV). The relation between the Present value, in year 0, and the Future Value, in year n, is given in Equation 1. The discount rate, i, is the most important parameter to define as it determines the size of the difference between FV and PV. The larger the discount rate the smaller is the PV of a given sum of money in k years. (Forte, 2012)

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

Calculation of Net Present Value

The most important indicator of the economics of an Energy Efficiency Project is the Net Present Value (NPV) as defined by Equation 2. It is defined as the sum of the Present Values of all the individual cost components discounted according to the year in which the cost in question occurs. As with the future costs, the NPV should take into account the future benefits.

As displayed in Equation 2 the best option would be the one giving the lowest NPV, i.e. “the minimum total costs”.

$$NPV = I_o + \sum_{n=1}^T \frac{C_n}{(1+i)^n} - \frac{B_n}{(1+i)^n} \quad 2)$$

I_o	The initial investment carried out in year 0
C_n	The total cost occurring in year n
B_n	The total benefits (revenues) occurring in year n
T	The time horizon

As the scenario analysis presented in the next chapter will be carried out for the period of 2014 – 2050, the economic analysis will consider this period as well. Hence, the period of analysis is not based on the buildings lifetime. The analysis will result in a NPV for each rehabilitation package as well as for the Base Case. The case with the lowest NPV will thus be the best financial solution.

Depreciation

Depreciation is used to reflect an items decreasing value with age. The reduced value is referred to as the items “book value “ or the “written down value” and is the value the item has at a particular moment in time. The simplest method of depreciation is straight line depreciation, where the items book value decrease by a constant amount each year over the effective life, starting from the acquisition cost and reaching zero at the end of the lifetime (Hastings, 2010). Whenever the period of analysis is shorter than the components lifetime, the component can be assumed to have a resale value at the end of this period(Standard Norge, 2013).

Payback time

The payback period is the time it takes before the investment is recouped by the generated return. It's calculated as the time it takes before the NPV of the cumulative returns exceed the initial investment. The Payback time is determined according to Equation 3 with the initial investment I_0 as a negative value and all future returns generated as positive values (pB_i). The year when the NPV becomes positive is thus the year when the investment is paid back, giving the payback time. (Hastings, 2010)

$$NPV = -I_0 + pB_1 + pB_2 + \dots + pB_n \quad 3)$$

3.4.3 Method and general assumptions

For each case the cost of both the passive and active measures will be taken into account in year 0. The analysis rests upon the basic assumption that the rehabilitation measures are only implemented when the building would require an upgrading. Thus, by comparing the NPV of each rehabilitation package to the Base Case both the best solution and the additional cost of rehabilitating to a better energy standard can be evaluated. Another assumption is that only the costs related to such measures that will influence the buildings energy balance is taken into account. However, to ensure the Base Case as a good foundation for comparison, some measures not related to the energy balance is included. On the following pages the most important assumptions for the base case and the power demand, along with the cost components can be found. Appendix G summarizes all assumptions made for the economic analysis and the sources the assumptions are based on. It also includes a table with all cost components used for the analysis.

The design power demand

In order to know the costs of the different energy supply systems the power requirement must be found. When calculating the design power demand for each rehabilitation case and the installed power required for the heat pumps and the boilers the equations given below has been used.

The design power required:

$$P_{dim} = \frac{H_{ve} \times (u_{int} - DUT) + H_{tr} \times (u_{int} - DUT)}{1000} \text{ [kW]} \quad 4)$$

$$P_{peak} = 0.4 \times P_{dim} \quad 5)$$

$$P_{base} = 0.6 \times P_{dim} \quad 6)$$

P_{dim}	Design power requirement to cover heating demand [kW]
H_{ve}	Overall heat transfer coefficient by ventilation [W/K]
H_{tr}	Overall heat transfer coefficient by transmission through thermal envelope [W/K]
u_{int}	Indoor temperature [°C]
DUT	Design outdoor temperature [°C]

Mechanical ventilation with heat recovery will lower the energy demand to the building, and thus also the power demand. According to Novacovic et al. this can be taken into account by using a factor $f_{v,i}$ as shown in the Equation 7 and 8.

$$P_{dim} = \frac{H_{ve} \times f_{v,i} \times (u_{int} - DUT) + H_{tr} \times (u_{int} - DUT)}{1000} \quad 7)$$

$$f_{v,i} = (1 - \eta_v) \quad 8)$$

η_v Heat recovery efficiency (0.7 for TEK 10 and 0.8 for Passive House)

The Base Case

The costs taken into account, in this case, are the energy costs as well as those components that influence the energy balance and reach their end of life before 2050. According to their technical lifetime some components might have to be changed before 2050, and this cost will be included in the Base Case to ensure a good foundation to compare the rehabilitation packages.

In the base case changing the cladding and the windows will be included. Based on their respective lifetimes, it is assumed that both will have to be changed within a short time, even if no additional insulation of the walls is included. The base case is supposed to show the costs of not investing in a better thermal envelope or energy related measures. However, based on information from Mestervindu, the windows changed in the base case are assumed to have a better U-value compared to the original ones. This will change the energy balance, and therefore the energy costs related to the base case have been calculated based on an energy balance including better windows.

Even if balanced ventilation is not installed in a building it's assumed that the dwelling has the normal form of mechanical exhaust ventilation installed in kitchen and bathrooms. Based on the lifetimes for ventilation systems, given in Appendix G, it will have to be upgraded during the buildings lifetime. Therefore the cost of upgrading the mechanical ventilation

system is included in all packages where balance ventilation is not. This also holds for the Base Case.

The Base Case includes

- Windows and doors are changed
- Exterior cladding is changed
- New Wood stove is purchased
- New Domestic Hot Water Heater is put in place.
- New direct electric heating in place
- Upgrading the mechanical exhaust ventilation system

3.4.4 Systems of funding

As described in chapter 2.10.2 there exists financial funding for the private homeowners wanting to carry out energy rehabilitations in their home. Based on the energy balance of each rehabilitation package, the ones that meet the requirement for funding will be calculated, and the amount of funding will be included in the NPV.

The requirement for the funding is based on information in chapter 2.10.2, as well as the buildings floor area. To get funding for energy related upgrading of a dwelling, the total heat loss number for heat transmission and infiltration through the building envelope must be reduced by 30% and be less than the numbers given in Table 12. In addition the annual net energy demand can't exceed the numbers given in Table 13.

Table 12: Requirements on Heat Loss number for funding

Heat loss number	$H''_{tr,inf}$ ⁸ [W/(m ² K)]
Level 1	0.60
Level 2	0.81

Table 13 Requirement for maximum annual net energy demand

Levels	Annual net energy demand [kWh/m ²]			
	Requirement ⁹	> 1956	1956 – 1970	1970 – 1980
Level 1	$100 + 1600/A_{fl}$	111	111	110.5
Level 2	$125 + 1600/A_{fl}$	136	136	135

In addition to this funding, whenever waterborne space heating is installed, funding according to information given in chapter 2.10.2 is taken into account.

⁸ $H''_{tr,inf}$ is the heat loss number for transmission and infiltration heat losses through the thermal envelope [W/m²K]

⁹ A_{fl} is the heated part of the BRA

During the economic analysis only funding that is available for every homeowner will be taken into account. Thus only the funding from Enova will be included in the analysis.

3.4.5 Payback time

The payback time of the most interesting packages is calculated according to the information given in chapter 2.10. Two basic assumptions are made when carrying out the calculations. First the initial investment I_0 is the additional investment compared to the BC, and is only considered for the year 2014. Second the returns generated by the investment are calculated as the savings in yearly cost compared to BC. This means that the Payback time only display the additional payback time compared to the base case, and not the total payback time for the investment made.

Depreciation

If a component reach its end of life before 2050, reinvestment using the 2014 prices is carried out. If the reinvested component reach end of life after 2050, straight line depreciation is used.

The discount rate

The discount rate is set to 7% for all cases according to information provided by (Jensen et al., 2003), as the mid-point of the recommended values.

3.4.6 Outcome

Based on all the assumptions presented in the preceding chapters the economic analysis will be an NPV of each of the energy rehabilitation packages, in addition to the Base Case.

The cost of balanced ventilation was found to differ extensively between Norsk Prisbok (Norconsult and AS Bygganalyse, 2013) and information provided by Flexit AS(Sætra, 2014). This is assessed by calculating NPV for both cases.

A sensitivity analysis of the electricity price is performed to assess how influential this parameter is.

Based on the results the most attractive solutions will be chosen, and based on these an energy scenario model will be used to project possible future energy scenarios, for the Norwegian dwelling stock.

3.5 The Future scenario model

3.5.1 Scope and system boundary

The Future scenario model will be based on the work carried out by Nina Sandberg calculating future scenarios for the Norwegian dwelling stock. The main goal for this model is not to predict the future, rather to investigate possible future scenarios for the energy demand and associated emissions in the dwelling stock. Based on the outcome of the economic analysis different rehabilitation packages will be implemented in the stock to varying extent, and the implications for the future energy demand will be investigated

The work is only concerned with the current standing dwelling stock of single-family dwellings originating from before 1980. All new construction beyond year 2013 is not accounted for.

3.5.2 The Segmented building stock model

The model has been developed by Nina Holck Sandberg and Helge Brattebø at the Industrial Ecology Program at the Norwegian University of Science and Technology, in collaboration with Igor Sartori at the Department of Building Infrastructure at SINTEF. The energy demand for the dwelling stock is the stock size multiplied with the average energy intensity, and the total GHG emissions related to the dwelling stock, is likewise the stock size multiplied with the average emission intensity. Many studies, when developing future energy and emission scenarios for the dwelling stock, use detailed analyses on the energy and emission intensities, but use simple linear models for the development of the stock itself. This model provides a better forecasting of the future dwelling stock, thus a better foundation for developing future energy scenarios. Based on the long-term development in the input parameters population and persons per dwelling coupled with lifetime and renovation probability functions the model gives the long-term development of the dwelling stock. The model provides results both for segments of the stock and the total stock itself. The dwelling stock segments are defined by the dwelling type and the construction period, for detached and compact houses and five age cohorts covering the years 1800 – 2100. The dwelling type “detached houses” includes single-family dwellings, farmhouses, semi-detached houses, terraced houses and other residential houses with less than three stories. “Compact houses” include apartment blocks and other residential houses with three stories or more, in addition to dwellings in commercial buildings or institutional households.

This model facilitate the use of two different probability distributions, both Normal and Weibull distribution. The Normal distribution is easy to use and commonly used in previous

dynamic models. Sandberg et al. finds the Weibull distribution to be better suited for representing the mortality of dwelling stocks, while the Normal distribution is suited for the renovation of the dwelling stock. (Sandberg et al., 2014)

3.5.3 Methodology and assumptions for the Energy scenario model

The model developed by Sandberg et al. and presented in the preceding chapter provides the possible future stock development. Based on the results from the economic analysis the most likely rehabilitation packages will be implemented in the stock and possible future scenarios for the development of total energy demand will be developed. Most of the rehabilitation packages have an energy supply system heavily dependent on electricity. Therefore to investigate emission scenarios with increased use of biomass a scenario using package 4.4 will also be carried out, regardless of how economic this package is found to be. Additionally implementation of nearly Zero Energy rehabilitated buildings will be considered. As pointed out by studies as for instance (Rambøll AS and Xrgia AS, 2011) there exists barriers towards energy rehabilitation of buildings beyond the mere cost perspective. Thus, even if rehabilitation is economically viable over the period of analysis it does not ensure that the rehabilitation in question will be carried out on a large scale.

System boundary

The study has so far only focused on the net and delivered energy demand for space heating and domestic hot water heating. As described in chapter 2.5 the EPBD asks for primary energy calculations when assessing energy use in buildings. Even if this concept is yet not given much focus in Norway the focus from the EU level indicates the concept will become more important in the future. The concept is thus introduced and the future primary energy consumption is calculated based on the total operating energy demand for space heating and domestic hot water.

Calculating the building stock development and the resulting energy and emission scenario

The Segmented Building Stock Model provides much information regarding the future Norwegian dwelling stock, given both for the total stock and segmented on building types and age cohorts. In addition it also gives the number of total dwellings, constructed, renovated and demolished dwellings each year. 2013 is chosen as the starting point for this analysis to provide solid numbers for 2014 and onwards. The current building stock standing in 2013 was calculated by summing all buildings constructed and subtracting all buildings demolished during each of the time cohorts. Thus all construction and demolishing activities from the

start (1800) to year 1956 provides the basis for year 2013 for age cohort “>1956”, and so on for the two next age cohorts.

A renovation lifetime of 40 years has been assumed with a standard deviation of 10 years as a basis for calculating the energy and emission scenarios. To test how the renovation lifetime will influence the results the building stock is modeled for two additional renovation lifetimes, 20 years with a standard deviation of 5 years and 60 years with a standard deviation of 10 years.

The probability distributions used for the scenarios are the Weibull-distribution for the demolition rate and the Normal-distribution for the renovation rate.

The stock model provides information of the number of dwellings renovated each year, divided on age cohorts, which is accumulated for each year from 2014 – 2050. The new construction activities in each age cohort is added to the starting point (year 2013) giving the total dwellings for all years 2014 – 2050. By subtracting the accumulated renovated dwellings each year from the total stock the building stock is divided in those buildings that are renovated and those that still have their original state for each year.

The energy scenario is found by multiplying the number of buildings from the segmented building stock model with the energy balances found in the current project. The number of renovated buildings is multiplied with the energy balance of the rehabilitation package investigated while the number of unchanged buildings is multiplied with the original or the historically upgraded energy balances. Numbers from Enova, regarding the percentage of original and historically upgraded buildings are used when finding the total energy use for the non-renovated buildings. As the building type “detached dwellings” includes buildings as small houses and farmhouses the numbers given by the segmented building stock model is downsized using information from Enova which indicates the percentage of single-family dwellings and small houses (Mjønes et al., 2012).

Emission and primary energy scenarios are found by multiplying the emission intensities and primary energy factors of each energy carrier with the corresponding energy use as found by the method described above. These factors are described in the next subsection.

Primary energy and CO₂ emission analysis

For the scenario analysis primary energy and CO₂ emissions is calculated based on NS-EN 15603 (Norsk Standard, 2008).

The primary energy related to a buildings energy use is calculated as defined by Equation 9.

$$E_P = \sum (E_{del,i} \times f_{P,del,i}) - \sum (E_{exp,i} \times f_{P,exp,i}) \quad 9)$$

$E_{del,i}$ The delivered energy for energy carrier i [kWh]

$E_{exp,i}$ The exported energy for energy carrier i [kWh]

$f_{P,del,i}$ The primary energy factor for the delivered energy carrier i
[kWh_{primary energy}/ kWh]

$f_{P,exp,i}$ The primary energy factor for the exported energy carrier i
[kWh_{primary energy}/ kWh]

A primary energy factor (PEF) is defined as the energy relationship between primary and secondary energy. Secondary energy is here defined as the delivered energy. It's used to illustrate the amount of primary energy which is indirectly caused by the consumption of the secondary energy (Adapt Consulting AS, 2012).

Table 14: PEF for different energy carriers and electricity mixes

Energy carrier	Primary energy factor f_P [kWh _{primary En.} /kWh]	Source
Norwegian electricity mix	1.19 ¹⁰	(Adapt Consulting AS, 2012)
Nordic electricity mix	1.74 ¹¹	(Värmeforsk, 2011)
UCPTE electricity mix	3.31	(Norsk Standard, 2008)
Wood	1.10	(Norsk Standard, 2008)
Bio-pellets	1.18	(Aalerud, 2012)
PV-panel	0.6 ¹²	(Gibon, 2014)

¹⁰ Chosen because it was calculated based on the model characterized as giving the best PEF.

¹¹ Based on information from table 3.12 in the given source which contains different PEF for Nordic el.mix based on different sources. This PEF was chosen because it was based on the most recent information. The value is given as the total PEF (including the renewable part)

¹² Doesn't include the renewable part as the other factors does.

The GHG emissions are calculated as CO₂-eq according to NS-EN 15603 (Norsk Standard, 2008) as defined by Equation 10.

$$m_{CO_2} = \sum (E_{del,i} \times K_{del,i}) - \sum (E_{exp,i} \times K_{exp,i}) \quad 10)$$

m_{CO_2}	Total GHG emissions resulting from the dwelling sector [ton CO ₂ -eq/m ²]
$E_{del,i}$	Delivered energy demand [kWh/m ²]
$K_{del,i}$	Emission intensity of energy carrier used to deliver $E_{del,i}$
$E_{exp,i}$ ¹³	Exported energy (the energy produced on site) [kWh/m ²]
$K_{exp,i}$	Emission intensity of energy carrier ¹⁴ used to produce the exported energy $E_{exp,i}$

The CO₂-emissions used for the emission scenarios are as follows:

Table 15: GHG-emission factors (Klimakalkulatoren, 2012) and (Fthenakis et al., 2011)

Energy carrier	Emissions [g. CO ₂ -eq /kWh]
Norwegian electricity mix	50
Nordic electricity mix	200
EU 27 electricity mix	542
Wood	261
Bio-pellets	261 ¹⁵
PV-panel ¹⁶	-28 ¹⁷

¹³ Only rehabilitation package R 5.0 includes energy production on site, in all other cases this parameter equals zero.

¹⁴ The energy carrier used for production is PV-produce electricity

¹⁵ Assumed the same values as given for wood.

¹⁶ The source for the emissions from PV-panel production: (Fthenakis et al 2011).

¹⁷ Negative value because the energy is produced on site

Outcome

The results from the scenario analysis will show the energy and emission scenario if each of the rehabilitation packages were fully implemented, meaning if they are carried out on all rehabilitated buildings. During the energy scenario analysis primary energy will be also be taken into account for the packages investigated. The resulting energy savings when implementing the different rehabilitation packages are compared both with and without primary energy taken into account.

The emission analysis evaluates the total emissions and accumulated savings of implementing the various rehabilitation packages, depending on the electricity mix used. A sensitivity analysis using the information from (Graabak and Feilberg, 2011) is carried out as well.

4 Results

4.1 The energy balance

This chapter contains a selection of the graphs and tables generated from the energy balance model. Additional results are included in Appendix E.

4.1.1 Specific energy demand for the original cases

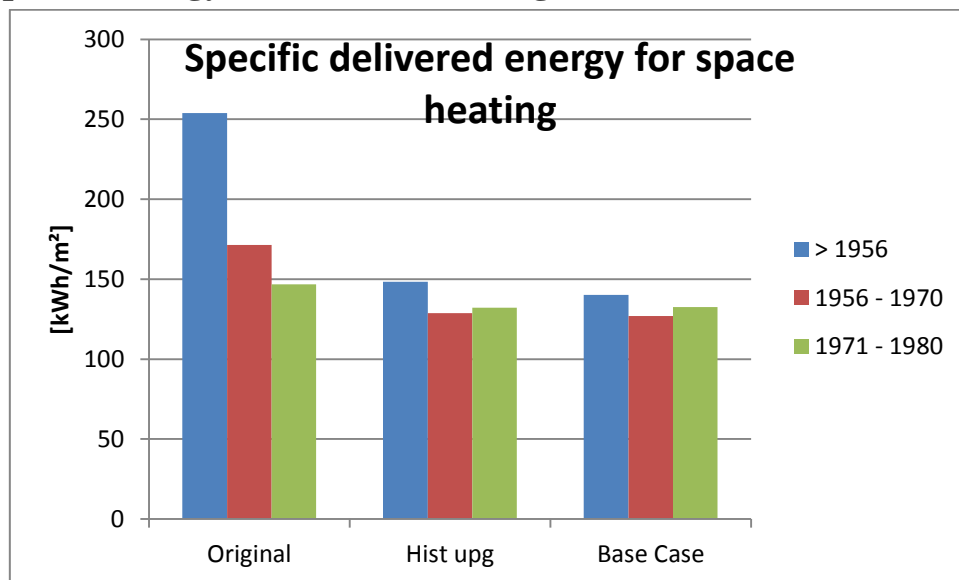


Figure 10: Specific delivered energy for space heating

As seen from Figure 10 the assumptions for the base case greatly reduces the energy demand for the buildings from the first two age cohorts compared to the original energy demand

4.1.2 Annual specific energy demand

The annual specific energy demand has been calculated both as the net and delivered energy demand, as well as the specific electricity demand.

Net energy demand

The annual net specific energy demand is given in Figure 11. Passive House and nZEnB rehabilitation induces the greatest energy reductions.

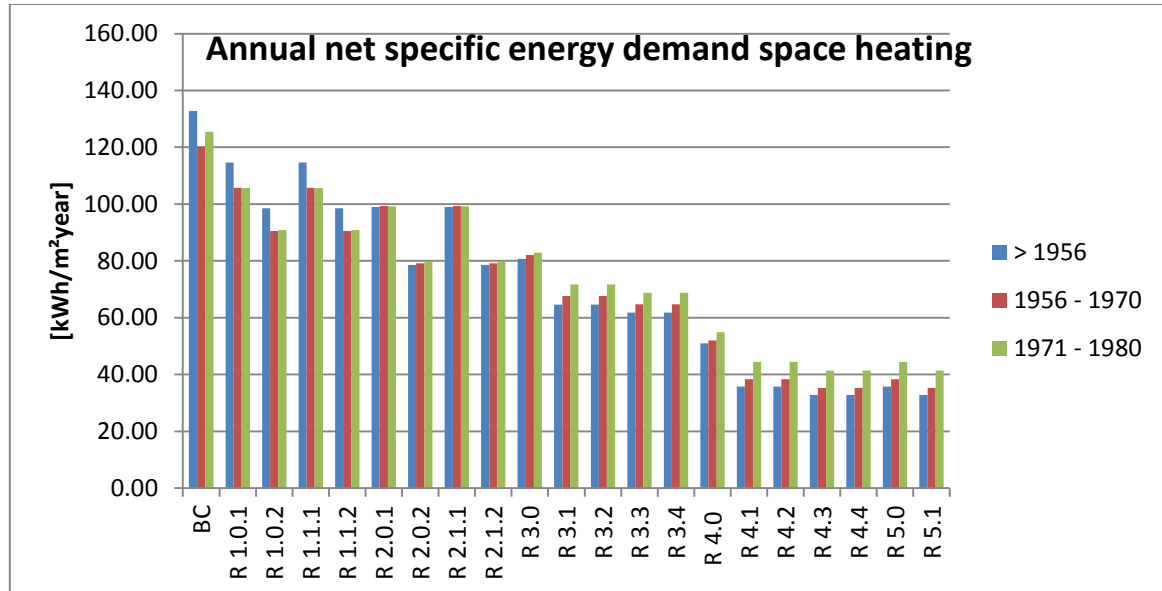


Figure 11: Annual net specific energy demand for space heating

Delivered energy demand

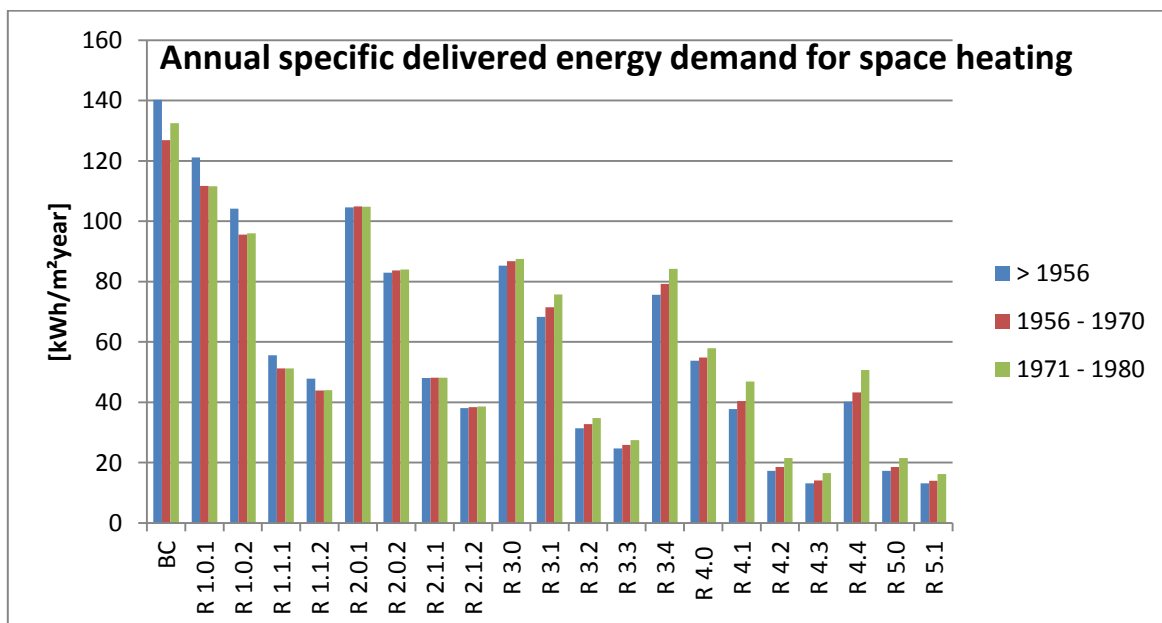


Figure 12: Delivered energy demand for space heating¹⁸

¹⁸ The energy demand for package 5.0 and 5.1 show the energy demand needed to cover space heating. Over the year the idea is that the same amount of energy can be produced on-site by PV-panels. This will ensure a nearly Zero Energy Building.

Total specific electricity demand

Calculations of the total specific electricity demand are given in Figure 13. Comparing this to Figure 12 it is evident that almost all cases are heavily dependent on electricity. R 3.4 and R 4.4 have significantly lower electricity demand as pellets boiler is used to cover base load for both space heating and DHW.

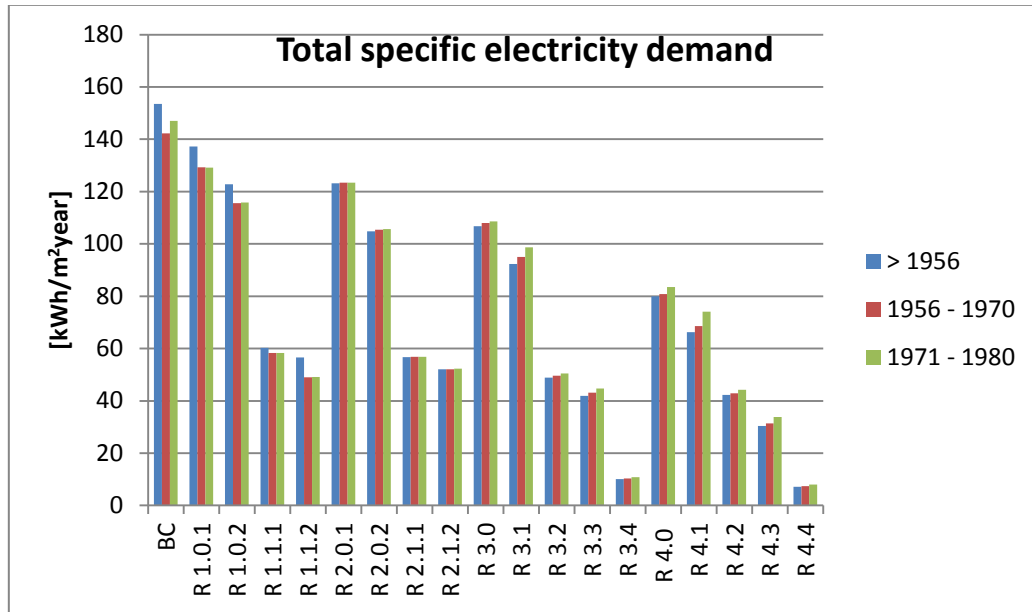


Figure 13: Specific electricity demand for space heating and DHW¹⁹

4.1.3 Packages that will receive financial funding

Based on the specific net energy demand as displayed in Figure 11 and the heat loss numbers given in Table 16 the packages that fulfill the requirements for “Funding for upgrading the dwelling” are rehabilitation packages belonging to group 4 and 5.

Table 16: Heat loss number for rehabilitation packages 4 and 5

	Heat loss number for Rehabilitation package 4 and 5		
	> 1956	1956 – 1970	1971 – 1980
$H''_{tr,inf}$ [W/m ² K]	0.71	0.67	0.73

¹⁹ Package 5.0 and 5.1 is not shown here as the net electricity demand over the year will amount to zero due to the PV-panels.

4.1.4 Reaching the energy requirements of TEK 10 and NS 3700

Table 17: Energy requirements of TEK 10 and Passive House (NS 3700), all numbers in [kWh/m² year]

	> 1956	1956 – 1970	1971 – 1980	
TEK 10	131	131	130.5	* Total net En. demand based on NS 3031
NS 3700	20.6	20.6	20.3	* Net En. demand for space heating based on NS 3031

To assess whether or not the rehabilitated buildings achieve the energy requirements given in TEK 10 and NS 3700 the energy demand for each building was compared to the standard requirements given in Table 17.

As can be seen from Table 18 the TEK 10 rehabilitated envelopes generally manage the TEK 10 energy requirements as long as balanced ventilation is used. As seen by Table 18 Passive House rehabilitated envelopes will also manage the TEK 10 requirement.

Table 18: Rehabilitation packages which reach the TEK 10 energy requirement, all numbers in [kWh/m² year]

	> 1956	1956 - 1970	1971 - 1980
R 3.0	139.4	140.7	141.5
R 3.1	123.3	126.4	130.4
R 3.2	123.3	126.4	130.4
R 3.3	120.4	123.4	127.4
R 3.4	120.4	123.4	127.4
R 4.0	109.6	110.6	113.6
R 4.1	94.4	97.0	103.1
R 4.2	94.4	97.0	103.1
R 4.3	91.5	94.0	100.1
R 4.4	91.5	94.0	100.1
R 5.0	94.4	97.0	103.1
R 5.1	91.5	94.0	100.1

The situation is quite another for the Passive House rehabilitated envelopes as given by Table 19. Here none of the buildings reach the Passive House energy requirement, and it is mainly due to the thermal bridging factor, which is much higher in this work than supposed by NS 3700.

Table 19: P.H rehabilitation with two different ΔU_{tbr} , all numbers in [kWh/m² year]

	P.H rehab with $\Delta U_{tbr} = 0.10$			P.H rehab with $\Delta U_{tbr} = 0.03$		
	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980
R 4.1	35.7	38.3	44.4	18.6	20.4	26.9
R 4.2	35.7	38.3	44.4	18.6	20.4	26.9
R 4.3	32.8	35.3	41.4	15.7	17.5	23.9
R 4.4	32.8	35.3	41.4	15.7	17.5	23.9
R 5.0	35.7	38.3	44.4	18.6	20.4	26.9
R 5.1	32.8	35.3	41.4	15.7	17.5	23.9

Table 20: Sensitivity analysis of changing ΔU_{tbr}

Sensitivity analysis of changing the ΔU_{tbr}			
	> 1956	1956 - 1970	1971 - 1980
R 4.1	48 %	47 %	39 %
R 4.2	48 %	47 %	39 %
R 4.3	52 %	51 %	42 %
R 4.4	52 %	51 %	42 %
R 5.0	48 %	47 %	39 %
R 5.1	52 %	51 %	42 %

As seen by Table 20 a 70% decrease in the thermal bridging factor will induce 40 – 50 % decrease in energy demand for Passive House rehabilitation.

4.2 The Economic analysis

For all cases the NPV was calculated based on the method described in chapter 3.4. By comparing the NPV of each rehabilitation package to the NPV of the Base Case the additional cost of each package was found. A positive additional cost means the package has an increased cost compared to the Base Case over the period of analysis, while a negative additional cost means the package is economically beneficial compared to BC. As long as it's not stated otherwise the analysis has been carried out including financial funding for those packages that will receive funding according to 4.1.3. The NPV of each rehabilitation package can be found in Appendix H

4.2.1 The Net Present Value additional cost compared to BC.

As explained in chapter 3.4.6 two prices deviating extensively were found for the balanced ventilation system. Therefore the resulting NPVs have been calculated using both prices. The results when using the price from Norsk Prisbok is marked with (N.P), while those based on the price from Flexit is marked with (Flexit). As can be seen by comparing Figure 14 and Figure 15 the cost of balanced ventilation influence which package that becomes economically viable.

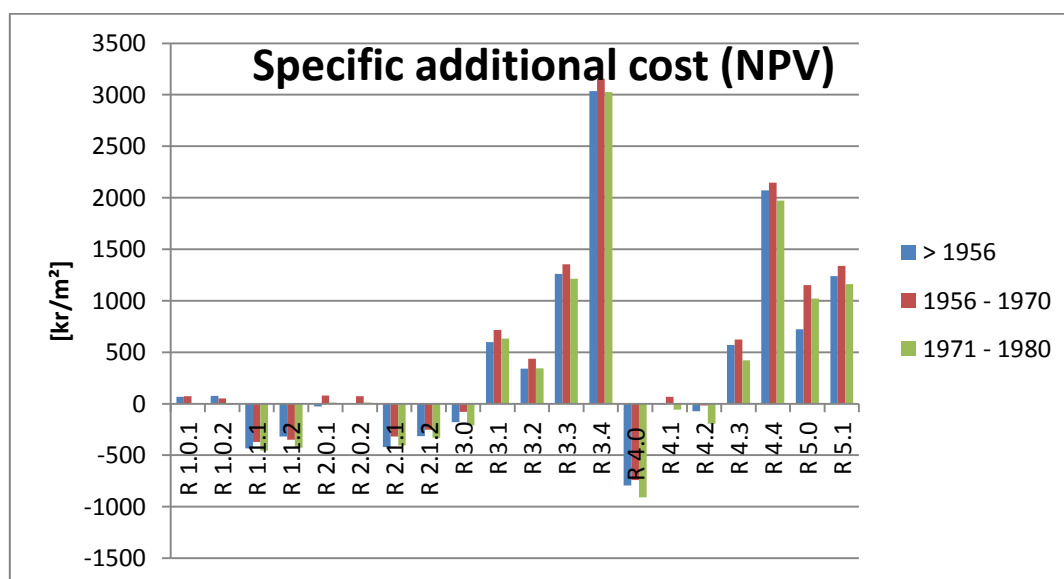


Figure 14: Specific additional cost (N.P)

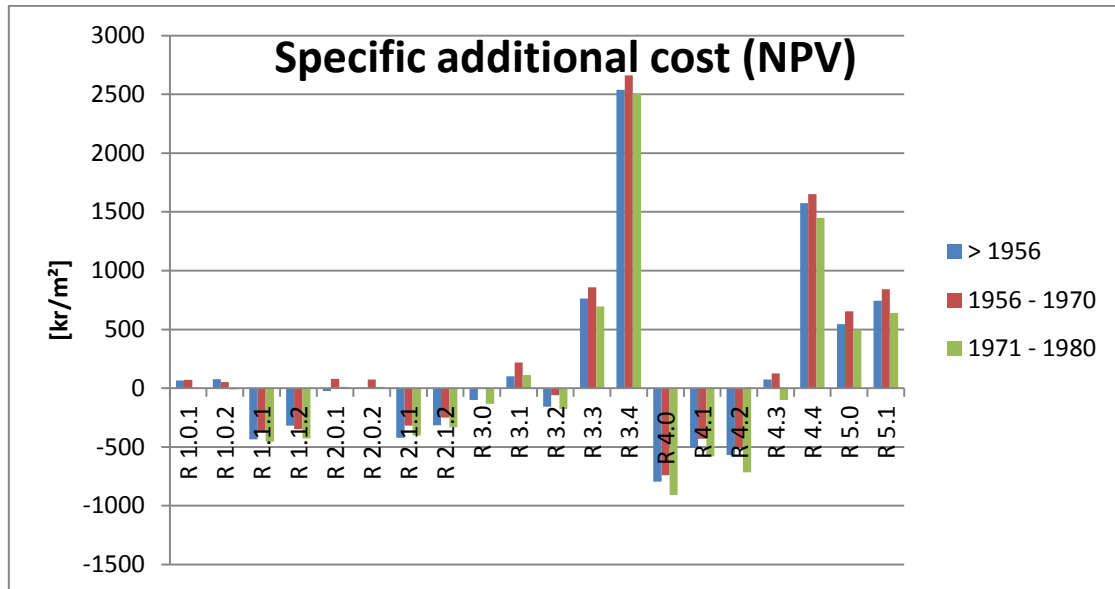


Figure 15: Specific additional cost (Flexit)

NPV if no financial funding is available

Financial funding has been applied in this analysis as it is currently provided (chapter 2.10.2). However, to assess whether or not the packages are economically beneficial without the funding this has been calculated as displayed in Figure 16.

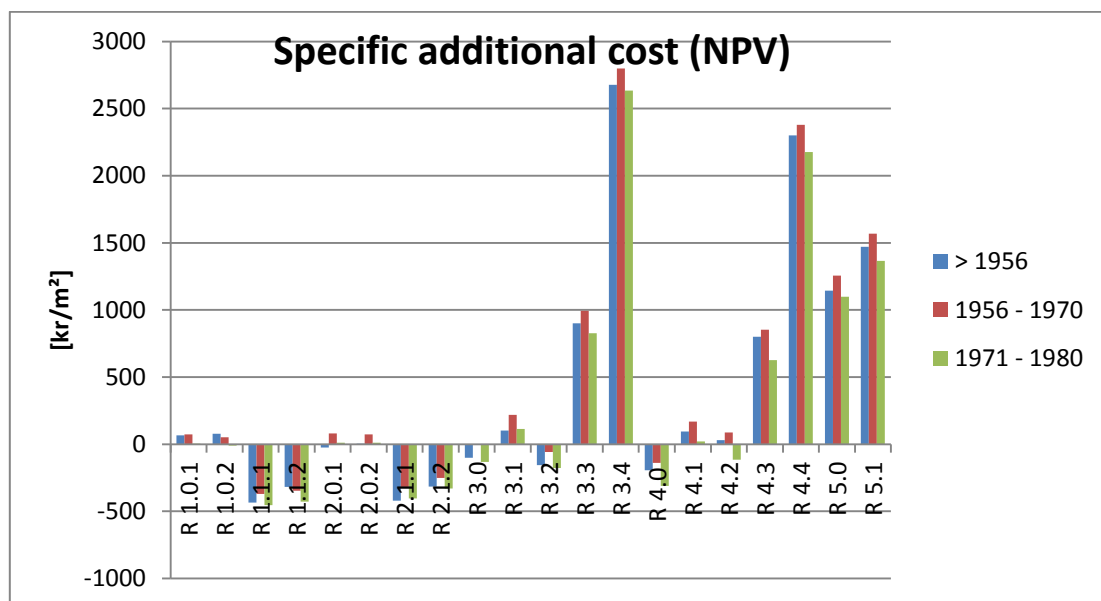


Figure 16: Specific additional cost without financial funding (using Flexit ventilation system)

4.2.2 Sensitivity analysis of the costs

Most of the packages are heavily dependent on electricity as displayed in Figure 13. It's therefore interesting to assess how the profitability of the packages change with increasing electricity price. This is depicted graphically in Figure 17 and numerically with the associated percentage increases in Table 21.

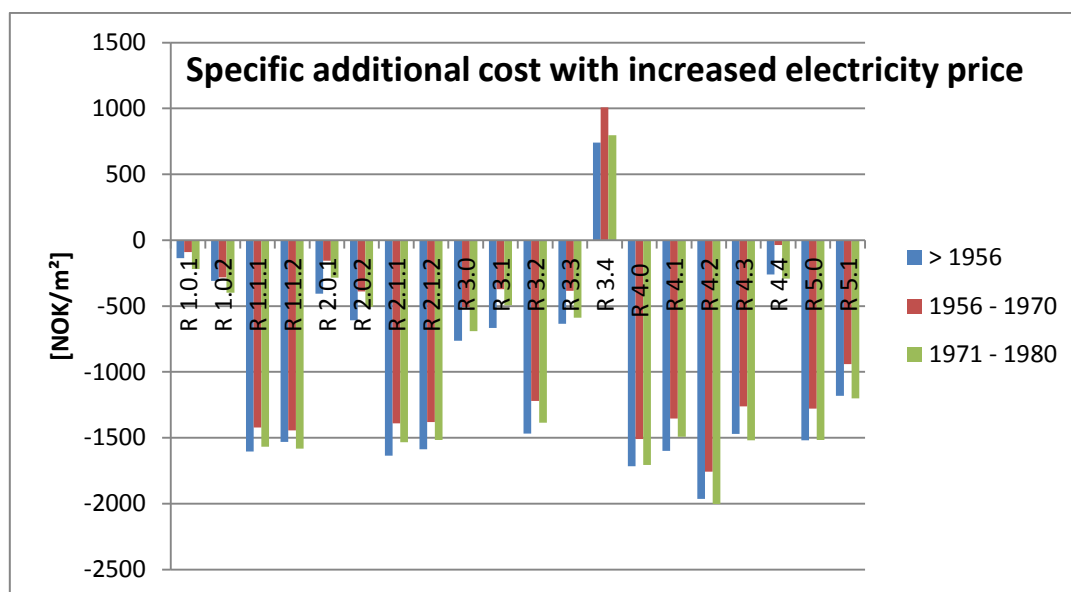


Figure 17: Additional cost with increased electricity price

Table 21: The change in NPV as a result of a 100% increase in the electricity price all years

Change in NPV as a result from 100% increase in electricity price			
	> 1956	56 - 70	71 - 80
BC	36 %	38 %	39 %
R 1.0.1	32 %	34 %	34 %
R 1.0.2	29 %	30 %	31 %
R 1.1.1	16 %	17 %	17 %
R 1.1.2	14 %	16 %	16 %
R 2.0.1	29 %	32 %	32 %
R 2.0.2	25 %	27 %	28 %
R 2.1.1	15 %	16 %	16 %
R 2.1.2	13 %	15 %	15 %
R 3.0	24 %	27 %	28 %
R 3.1	21 %	24 %	25 %
R 3.2	12 %	13 %	14 %
R 3.3	9 %	10 %	10 %
R 3.4	2 %	2 %	2 %
R 4.0	22 %	25 %	27 %
R 4.1	17 %	20 %	22 %
R 4.2	11 %	13 %	14 %
R 4.3	7 %	8 %	9 %
R 4.4	1 %	1 %	2 %
R 5.0	-2 %	-3 %	-3 %
R 5.1	0 %	0 %	0 %

4.2.3 Analysis of the cost components

This section focus on the costs related to the different components both for the Base Case, TEK 10 and Passive House rehabilitation. The windows are generally associated with high costs, thus the additional cost of upgrading the windows is small. Installing a waterborne space heating system is very costly especially for TEK 10 rehabilitation, which is due to the price used for this system. This is thoroughly discussed in chapter 5.2.

Base Case

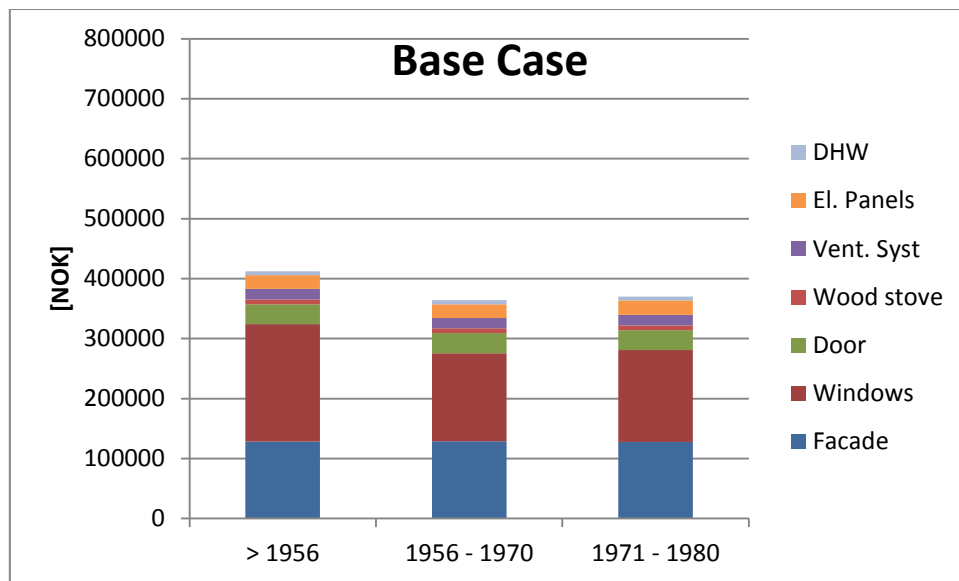


Figure 18: Investment cost components, Base Case

TEK 10 and Passive House rehabilitations

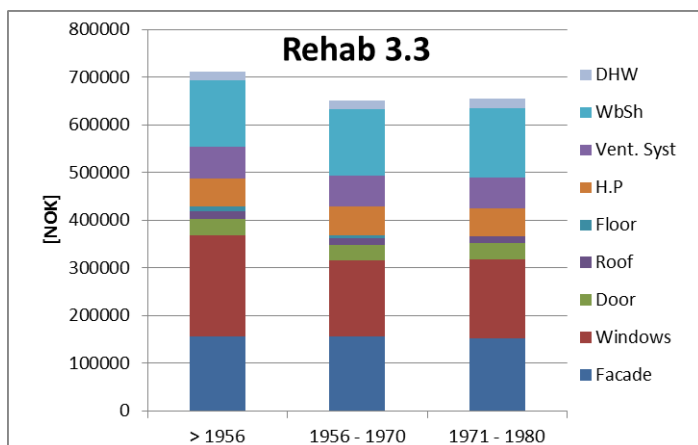


Figure 19: Investment cost components rehab. package 3.3

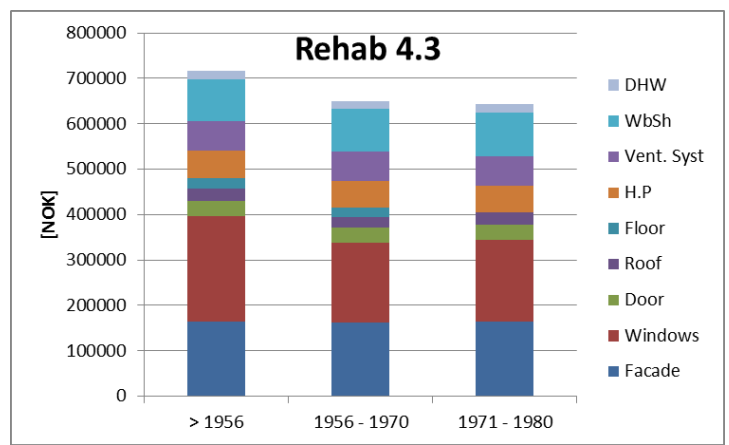


Figure 20: Investment components rehab. package 4.3

Comparison of the cost components to BC

A comparison of the cost components in year 2014, is given in Table 22. Comparing these costs to those of Figure 18 show that the additional cost of better windows and walls are small compared to the initial cost of changing windows or fixing the façade.

Table 22: Investment costs compared to BC

	Rehab. package 3			Rehab. package 4		
	> 1956	56 - 70	71 - 80	> 1956	56 - 70	71 - 80
Facade	27655	27134	24291	35771	33996	35657
Windows	17323	12992	13526	36715	27537	28668
Door	0	0	0	0	0	0 ²⁰
Roof	16363	13370	13919	27401	24510	25517
Floor	10656	6685	0	23606	20716	0 ²¹
Tot. buidling upgrade	71998	60181	51736	123493	106758	89842

4.2.4 Payback time

Table 23: The Payback time of four rehabilitation packages compared to Base Case.

Rehabilitation package	Payback time compared to Base Case
R 1.1.1	5 years
R 4.2	20 years
R 4.4	Not paid back within year 2050
R 5.0	Not paid back within year 2050

The Payback time only takes into account the total investment made in year 2014 and how many years it will take before this investment is paid back. Thus reinvestments occurring during the period of analysis are not considered. Hence the results are only meant to provide some insights to how long the payback time can be, and must therefore not be considered a thorough analysis of the payback time.

²⁰ Doors were given the same cost for all cases, therefore 0 here.

²¹ Floors not upgraded for the cohort 70 – 80

4.3 The Future scenario model

This chapter provides the main results from the scenario analysis. Further results are attached in Appendix I.

4.3.1 The development of the Norwegian dwelling stock

Figure 21 depicts the increase in both the total Norwegian dwelling stock as well as for compact and detached buildings, as found by (Sandberg et al., 2014). Detached dwellings include single-family dwellings and farm houses. The figure has been enclosed only to provide information about the development of the entire dwelling stock as found by Sandberg et al. It doesn't provide any information regarding the results found during the current work. For the remaining part of this work the focus has been on the existing detached dwelling stock from 2013, thus disregarding both the compact dwellings and new construction of detached dwellings.

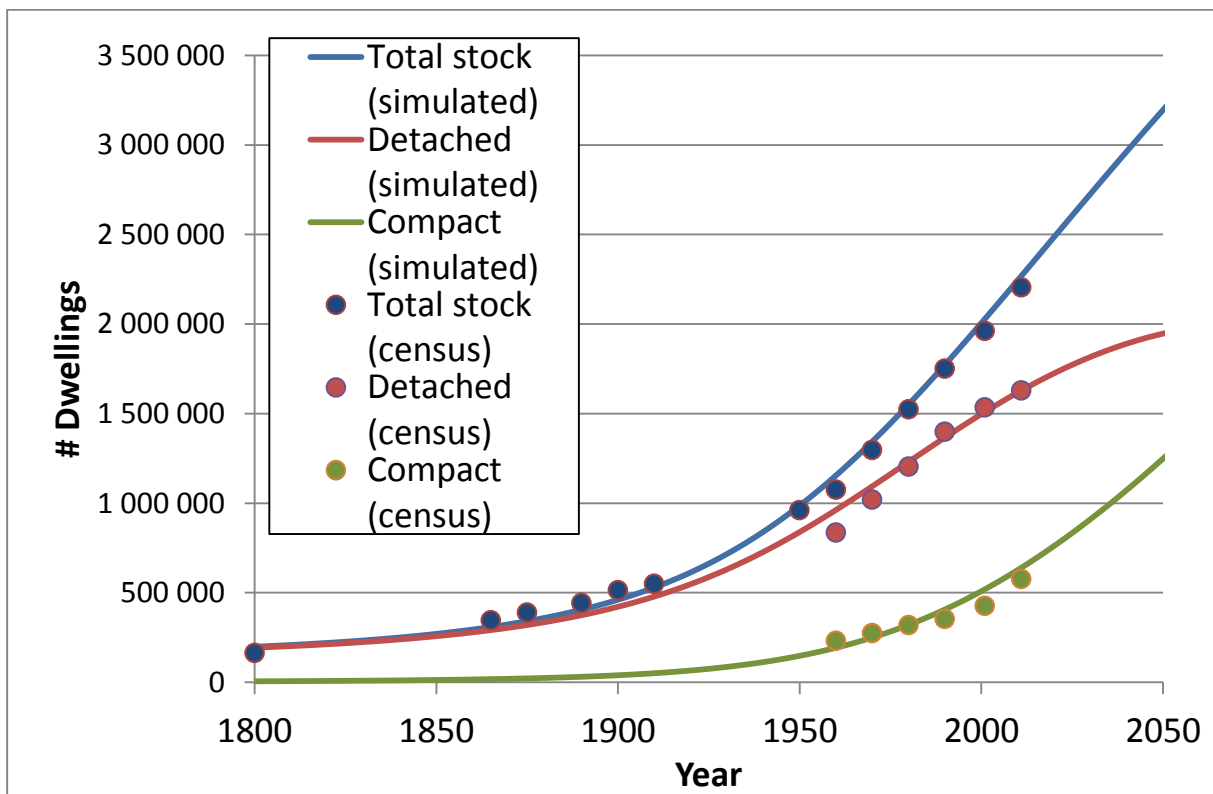


Figure 21: The development in the entire Norwegian building stock (Sandberg et al., 2014)

4.3.2 The renovation development in detached dwellings

During the rest of the analysis new dwellings built after 2013 are not included, thus the following figures will only provide information about the development in the existing detached dwelling stock depending on the renovation rates and age cohorts.

Development using a renovation lifetime of 40 years and a standard deviation of 10 years

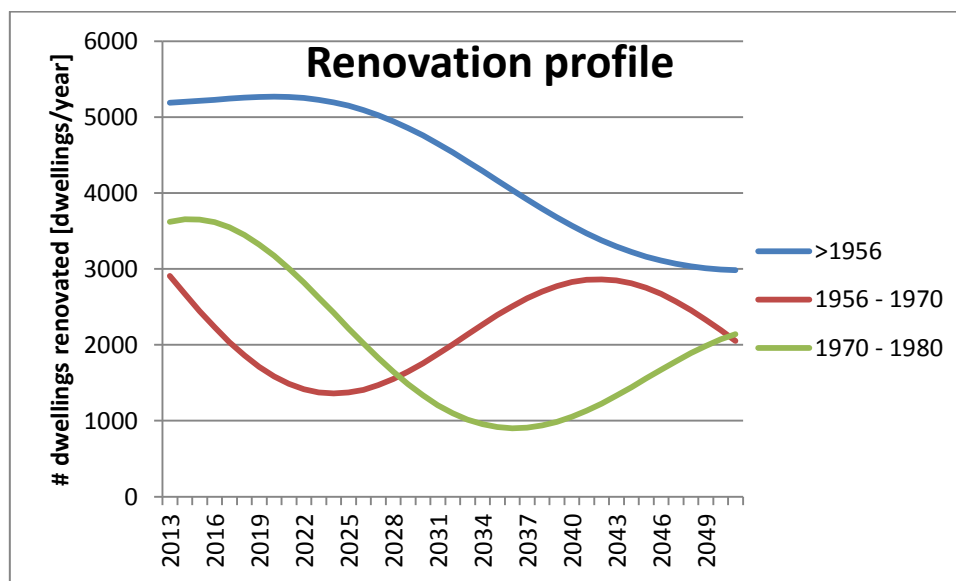


Figure 22: The renovation profiles for Single-Family dwellings given a renovation lifetime of 40 years

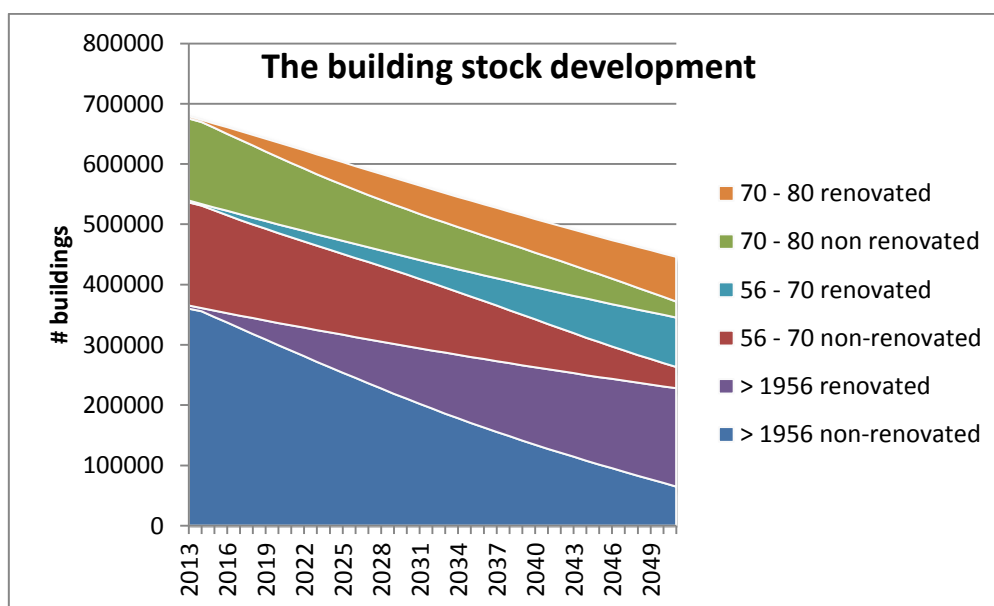


Figure 23: The development of Single-Family dwellings given a renovation lifetime of 40 years

Development using a renovation lifetime of 20 years and a standard deviation of 5 years

Using a short renovation lifetime will result in more renovations being carried out as seen in this section. It's interesting to note the development occurring in Figure 25. Here the amount of renovated buildings exceeds the non-renovated buildings. The accumulated unchanged buildings are calculated as described in chapter 3.5.3, and due to the frequent renovation profile the unchanged buildings approach zero and become negative around year 2036. Of course the stock itself isn't negative, this only means that the number of accumulated renovated dwellings exceed the total number of dwellings, which in turn indicates that dwellings are being renovated more than once. Hence the peculiar shape seen in Figure 25 which is further elaborated in chapter 5.3.

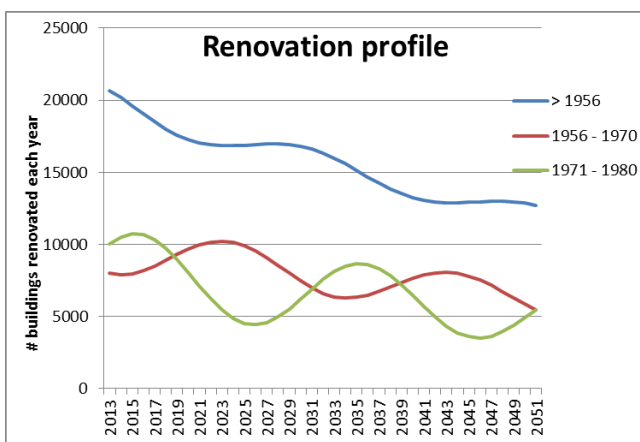


Figure 24: The renovation profiles for Single-Family dwellings given a renovation lifetime of 20 years

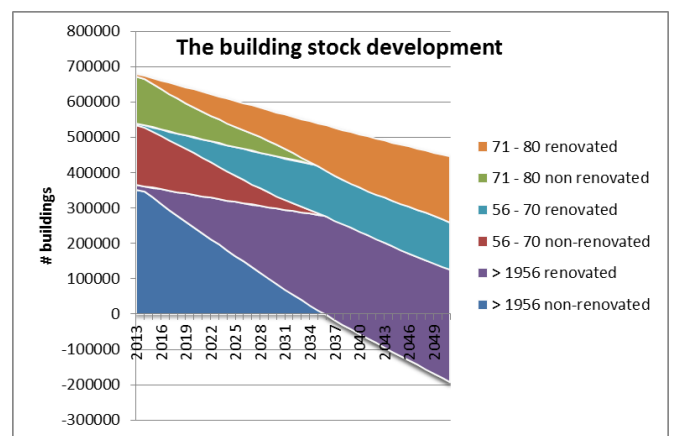


Figure 25: The development of Single-Family dwellings given a renovation lifetime of 20 years

Development using a renovation lifetime of 60 years and a standard deviation of 5 years

Using a longer renovation lifetime results in fewer buildings being renovated as seen by comparing Figure 27 to Figure 23. This especially influences the oldest age cohort.

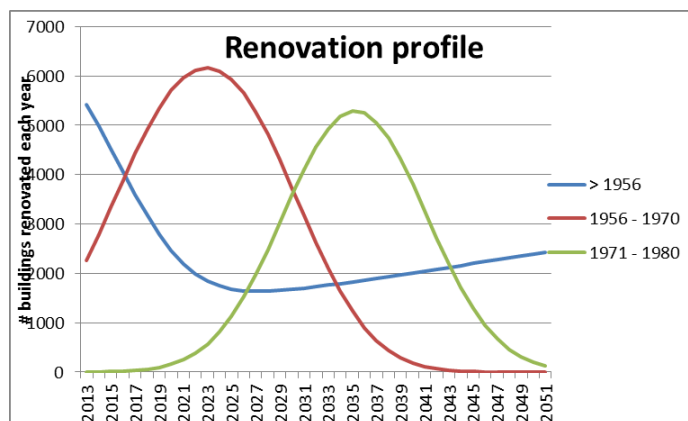


Figure 26: The renovation profiles for Single-Family dwellings given a renovation lifetime of 60 years

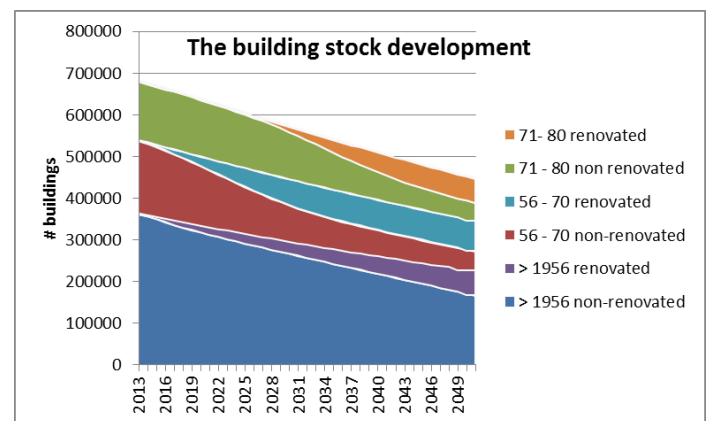


Figure 27: The development of Single-Family dwellings given a renovation lifetime of 60 years

4.3.3 Energy scenarios

This chapter includes the results from the energy scenario analysis. In both figures the energy demand for the entire stock is shown, i.e. it's not divided by age cohort. The energy scenario is based on a lifetime of 40 years with a standard deviation of 10 years. As for the preceding chapter the figures in the current chapter contain information regarding the existing detached dwelling stock from 2013 onwards. New construction has not been included in the calculations.

The scenarios considered are as follows:

- Scenario C0: All buildings at current state, no rehabilitations carried out, not even those required to maintain the current state
- Scenario C1: All renovated buildings are only renovated according to Base Case, unchanged buildings have an energy balance according to current state.
- Scenario C2: All renovated buildings are renovated according to R 1.1.1, unchanged buildings have an energy balance according to current state.
- Scenario C3: All renovated buildings are renovated according to R 4.2, unchanged buildings have an energy balance according to current state
- Scenario C4: All renovated buildings are renovated according to R 5.0, unchanged buildings have an energy balance according to current state
- Scenario C5: All renovated buildings are renovated according to R 4.4, unchanged buildings have an energy balance according to current state

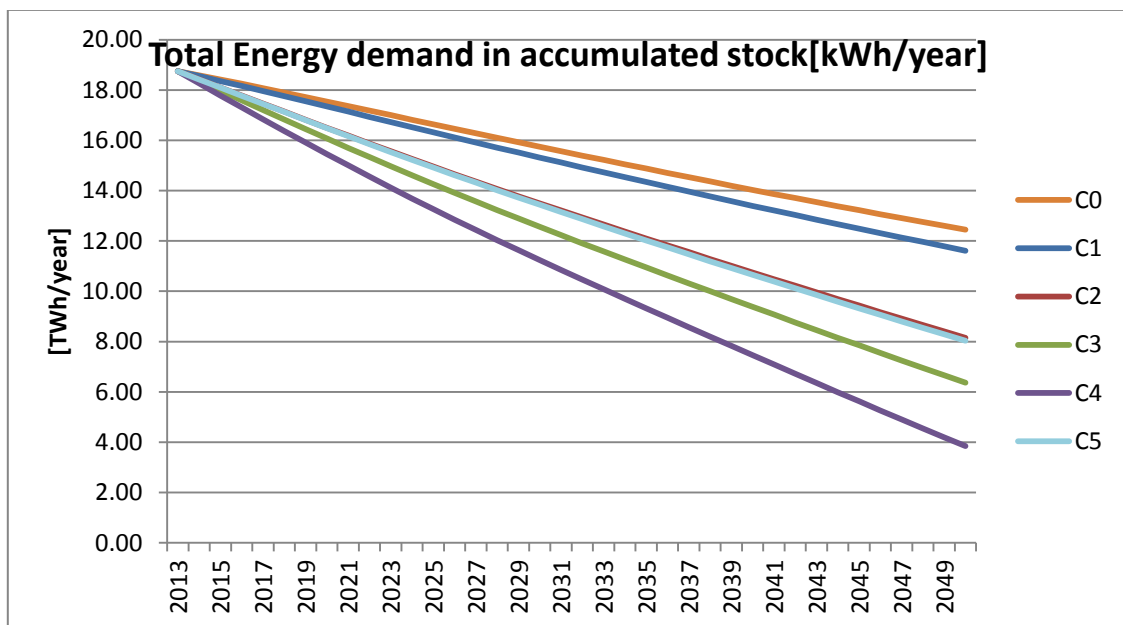


Figure 28: Yearly energy demand for each scenario for the entire stock (all three age cohorts)

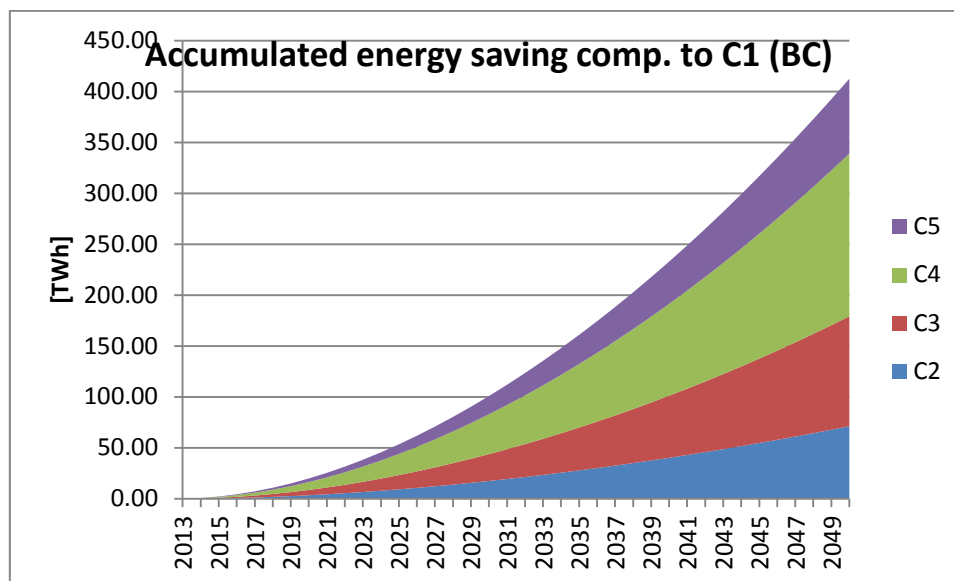


Figure 29: Accumulated energy savings compared to Base Case for the entire stock (all three age cohorts)

Table 24: Accumulated energy demand and energy savings

Scenario	Accumulated energy [TWh]		Decrease comp. to C1
	Energy demand	Energy saving comp. To C1	
C0	590		
C1	573	17	3 % ²²
C2	502	71	12 %
C3	465	108	19 %
C4	413	160	28 %
C5	500	74	13 %

Table 25: Energy demand in year 2050 given different scenarios

Scenario	Energy demand in 2050 [TWh]	
	Energy demand	Energy saving comp. to C1
C1	11.62	
C2	8.15	3.46
C3	6.37	5.25
C4	3.84	7.77
C5	8.04	3.58

The accumulated energy demand through the entire period, along with the possible savings if the different scenarios are implemented is displayed by Table 24. The accumulated energy savings have been calculated relative to C1 for all cases except for C1 itself, which is relative to C0. The total energy demand for this part of the building stock occurring in 2050 is displayed in Table 25. The possible energy saving this year due to implementation of the different rehabilitation packages is shown as well.

²² The decrease for C1 is calculated as the decrease compared to C0

4.3.4 Primary energy analysis

This section gives results for the future accumulated energy demand when primary energy is taken into account. In addition Table 28 provides an overview of how the different electricity mixes influence the energy balance of rehabilitation package R 5.0. This package was created such that the PV-production of electricity would balance the buildings annual energy demand.

Table 26: Accumulated delivered and Primary Energy, with Norwegian, Nordic and EU electricity mixes

Scenario	Delivered energy [TWh]	Primary energy [TWh]			Primary energy increase compared to delivered energy		
		Norwegian	Nordic	EU	Norwegian	Nordic	EU
C1	5.73E+02	6.76E+02	8.33E+02	1.75E+03	18 %	45 %	205 %
C2	5.02E+02	5.90E+02	7.20E+02	1.48E+03	18 %	44 %	195 %
C3	4.65E+02	5.48E+02	6.74E+02	1.41E+03	18 %	45 %	202 %
C4	4.13E+02	5.17E+02	6.43E+02	1.38E+03	25 %	55 %	233 %
C5	5.00E+02	5.89E+02	7.05E+02	1.36E+03	18 %	41 %	172 %

Table 27: Sensitivity analysis of PEF for Norwegian electricity mix

Sensitivity analysis of PEF Norwegian el.mix			
Scenario	Base [TWh]	PEF doubled [TWh]	Increase
C1	6.76E+02	1.28E+03	89 %
C2	5.90E+02	1.09E+03	85 %
C3	5.48E+02	1.03E+03	88 %
C4	5.17E+02	9.99E+02	93 %
C5	5.89E+02	1.03E+03	75 %

The accumulated energy demand is presented in Table 26, both for the delivered and the primary energy demand using three different electricity mixes. As can be seen from the table, taking primary energy into account increase the accumulated energy demand and different electricity mixes greatly influence the results.

Sensitivity analysis of PEF for Norwegian electricity mix shows that increasing this value by 100% induce large increases in the accumulated primary energy demand for all scenarios, as seen by Table 27.

Table 28: Analysis of nearly zero-energy buildings when primary energy is taken into account

Delivered energy [kWh/ year]				
Cohort	Electricity	Wood	PV	Total
> 1956	6170	1628	-7798	0
56 - 70	6256	1747	-8003	0
71 - 80	6725	2108	-8833	0
Primary Energy (Norwegian) [kWh/building year]				
Cohort	Electricity	Wood	PV	Total
> 1956	7342	1791	-4679	4454
56 - 70	7445	1921	-4802	4564
71 - 80	8003	2318	-5300	5021
Primary Energy (Nordic) [kWh/building year]				
Cohort	Electricity	Wood	PV	Total
> 1956	9255	1791	-4679	6367
56 - 70	9384	1921	-4802	6504
71 - 80	10087	2318	-5300	7106
Primary Energy (European) [kWh/building year]				
Cohort	Electricity	Wood	PV	Total
> 1956	20422	1791	-4679	17534
56 - 70	20708	1921	-4802	17828
71 - 80	22259	2318	-5300	19278

As seen by Table 28 taking primary energy into account greatly affects the buildings energy balance, and in terms of primary energy the buildings will not be nearly Zero Energy Buildings.

4.3.5 Emission scenarios

The results presented in this chapter depict the emission scenarios assuming a lifetime of 40 years with a standard deviation of 10 years. All figures in the current chapter provide information about the existing dwelling stock for detached dwellings from 2013 onwards.

Figure 30 gives an overview of how the total accumulated emissions differ when choosing different electricity mixes. On general terms it can be stated that using the European electricity mix greatly increase the estimated emissions compared to using the Norwegian electricity mix. As the European mix is associated with a much larger emission intensity this result is reasonable.

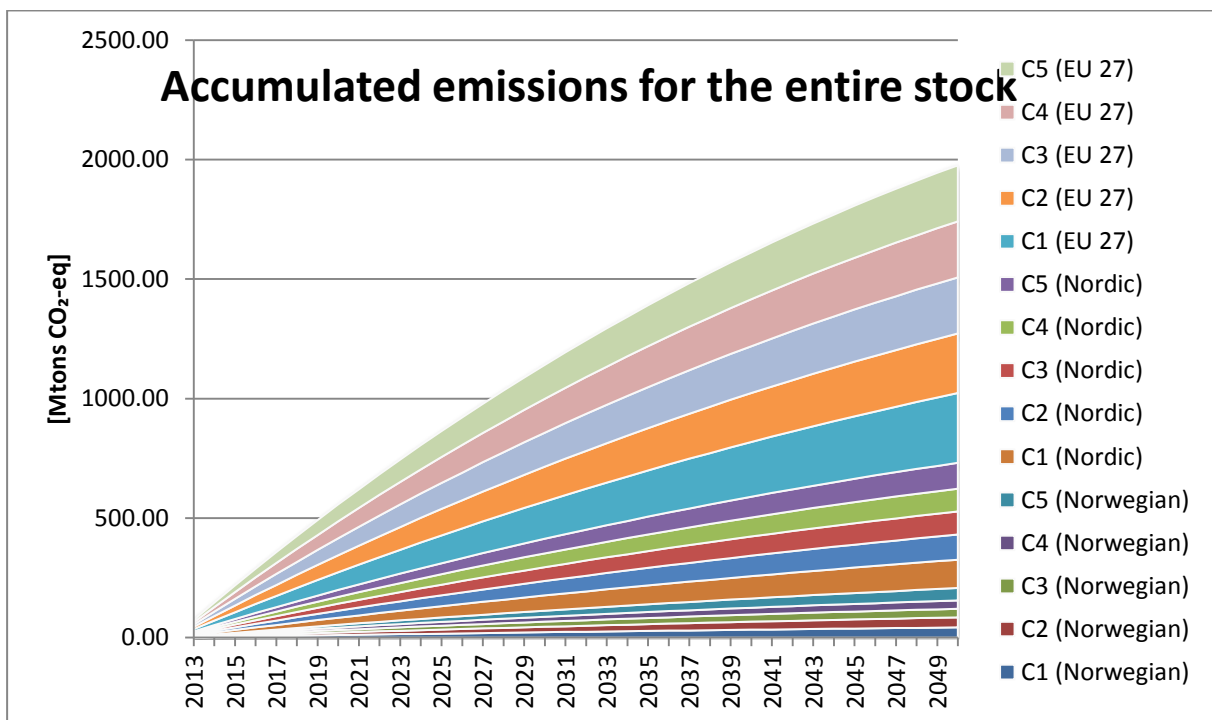


Figure 30: Emission scenarios for the stock for each electricity mix

Figure 31 and Figure 32 display's the accumulated emission savings of implementing each of the rehabilitation packages compared to the BC (C1) using Norwegian and European electricity mixes, respectively. As seen by Figure 31 the emissions related to C5, implementing rehabilitation package R 4.4 on all rehabilitated buildings, are greater than the emissions resulting from BC. This is due to the emission intensity attributed to biomass, which is quite high compared to that of the Norwegian electricity mix. Looking at Figure 32 it can be seen that scenario C5 will induce an emission saving compared to BC when using the European emission intensity. This is further elaborated in the discussion.

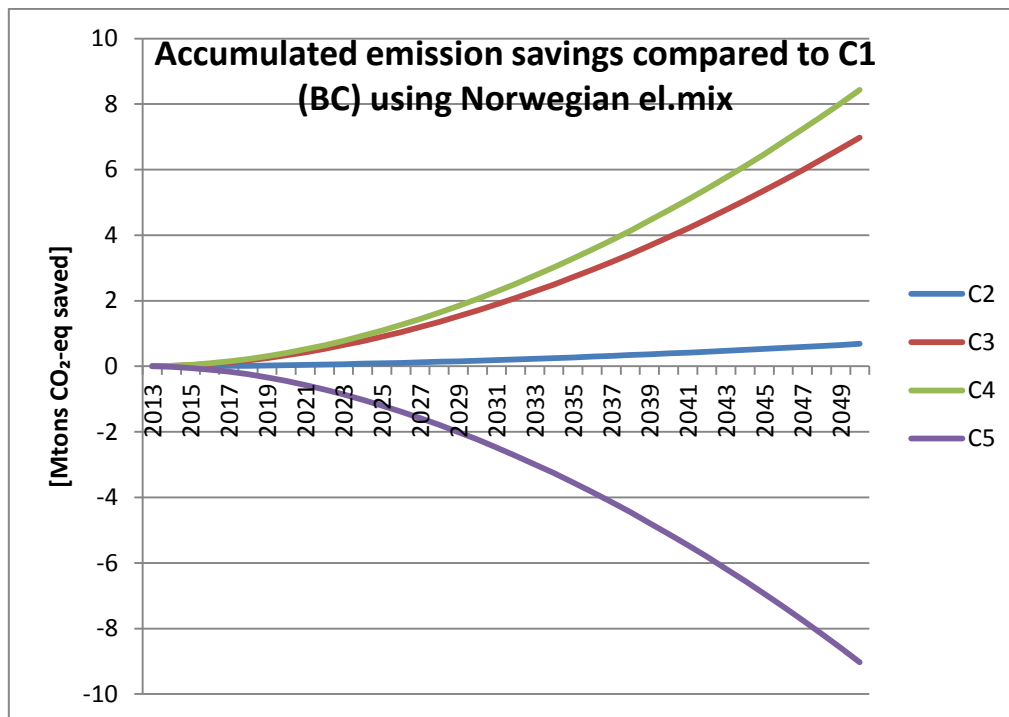


Figure 31: Accumulated emission savings with Norwegian el. Mix

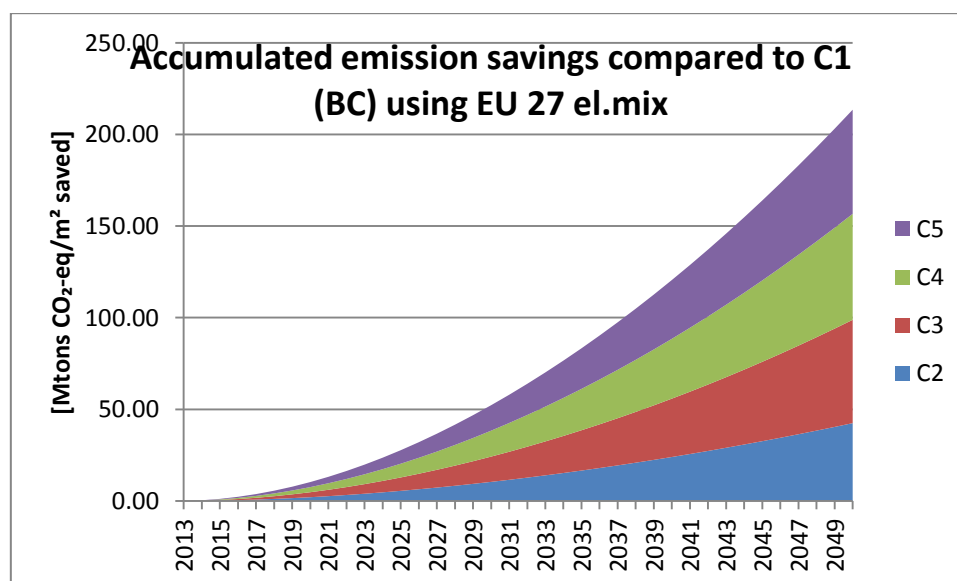


Figure 32: Accumulated emission savings using EU 27 el. mix

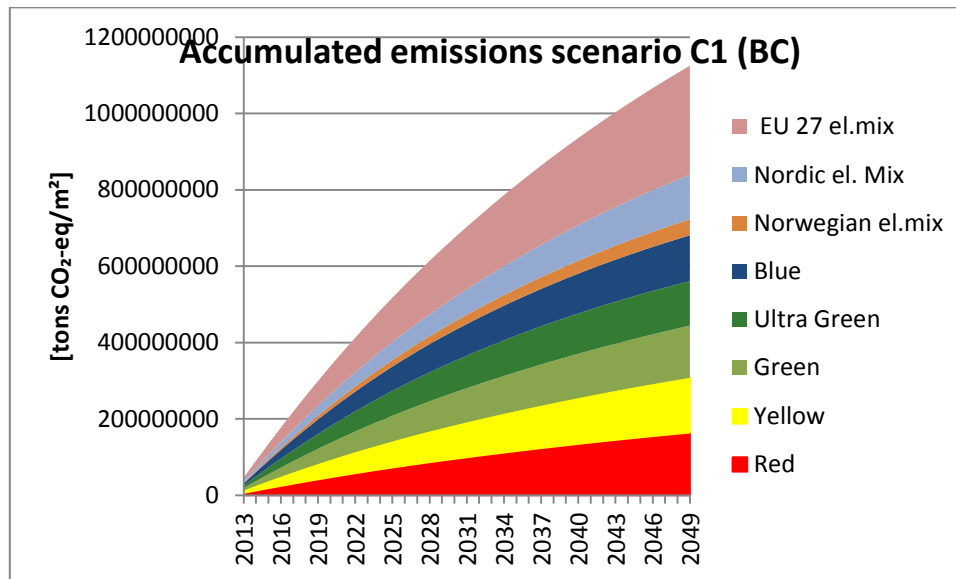


Figure 33: Accumulated emissions distributed on electricity mixes

By using the information provided by (Graabak and Feilberg, 2011) the accumulated emissions for the Base Case scenario was assessed. As displayed in Figure 33 the different scenarios will greatly influence the future emissions from the Norwegian building stock. The figure also gives the accumulated emissions using Norwegian, Nordic and European electricity mix. This provides information on how likely future emission scenarios for the European electricity mix influence the results compared to using the Norwegian mix.

To assess how much the accumulated emissions increase when basing the calculations on European or Nordic electricity mix instead of the Norwegian mix, the percentage increase of the these mixes compared to the Norwegian one is displayed in Table 29. As can be seen the accumulated emissions increase significantly when using Nordic mix, and even more so when using European mix.

Table 29: Percentage increase of accumulated CO₂-eq emissions using different electricity mixes

Percentage increase compared to Norwegian electricity mix					
	Norwegian [Mtons CO ₂]	Nordic [Mtons CO ₂]	EU 27 [Mtons CO ₂]	Nordic	EU 27
C1	43	119	292	177 %	579 %
C2	42	105	249	149 %	490 %
C3	36	97	235	169 %	555 %
C4	35	95	234	176 %	577 %
C5	52	108	235	107 %	352 %

4.3.6 The influence of lifetime distributions

The accumulated energy and emission savings of each rehabilitation package have been compared to the accumulated energy and emissions resulting from the Base Case, for three different renovation lifetimes, as can be seen in Table 30. It is evident from these results that the renovation lifetime chosen will influence the results regarding future energy and emission savings.

Table 30: Accumulated energy and emission savings for three different renovation lifetimes (using Norwegian el.mix)

Scenario	Accumulated Energy saving [TWh]			Accumulated Emission savings [Mton CO ₂ -eq]		
	40 (10)	20 (5) ²³	60 (5)	40 (10)	20 (5)	60 (5)
C2	71.3	250	60.1	0.684	1.74	0.39
C3	108	302	72.5	6.98	18.1	4.29
C4	160	415	100	8.43	21.9	5.23
C5	74.3	191	45.0	-9.03	-23.5	-6.00

²³ Caution: According to the results from the building stock model using a lifetime of 20 years results in buildings being renovated more than once. The current scenario model is not fit to take this into account, thus these results should be disregarded. This is elaborated in the discussion.

5 Discussion

Since there are many references to the rehabilitation packages in the following discussion a table is provided, giving a summary of the most important aspects of each rehabilitation package:

Table 31: Summary of all packages

Package	Thermal envelope upgrading	Active measures
Base Case	No rehabilitation except better windows	
R 1.0.1	TEK 10 rehabilitation of façade and windows	
R 1.0.2	P.H rehabilitation of façade and windows	
R 1.1.1	TEK 10 rehabilitation of façade and windows	Air-to-air heat pump
R 1.1.2	P.H rehabilitation of façade, windows and roof	Air-to-air heat pump
R 2.0.1	TEK 10 rehabilitation of façade and windows	
R 2.0.2	P.H rehabilitation of façade, windows and roof	
R 2.1.1	TEK 10 rehabilitation of façade and windows	Air-to-air heat pump
R 2.1.2	P.H rehabilitation of façade, windows and roof	Air-to-air heat pump
R 3.0	Full TEK 10 rehabilitation of all envelope elements (façade, windows, roof and floor ²⁴)	
R 3.1		Balanced ventilation
R 3.2		Balanced ventilation + air-to-air heat pump
R 3.3		Balanced ventilation + air-to-water heat pump
R 3.4		Balanced ventilation + biomass boiler
R 4.0	Full Passive House rehabilitation of all envelope elements (façade, windows, roof and floor ²⁵)	Balanced ventilation
R 4.1		Balanced ventilation + air-to-air heat pump
R 4.2		Balanced ventilation + air-to-water heat pump
R 4.3		Balanced ventilation + biomass boiler
R 4.4		
R 5.0	Full Passive House rehabilitation of all envelope elements (façade, windows, roof and floor ²⁶) (nZEnB)	Balanced ventilation + air-to-air heat pump + PV-panel
R 5.1		Balanced ventilation + air-to-water heat pump + PV-panel

²⁴ The floor is not rehabilitated for age cohort "1971 – 1980"

²⁵ The floor is not rehabilitated for age cohort "1971 – 1980"

²⁶ The floor is not rehabilitated for age cohort "1971 – 1980"

5.1 The Energy balance model

5.1.1 Energy and electricity demand

As seen by Figure 11 the annual net specific energy demand decrease as a result of rehabilitating the thermal envelope. Not surprisingly the measures inducing the largest reductions are those where the entire building envelope is rehabilitated, especially when these rehabilitations are at Passive House level. Moreover, installing balanced ventilation further reduce the energy demand with 5 – 10 kWh/m².

The delivered energy demand, seen in Figure 12 takes into account the efficiency of the space heating systems. As can be seen from this figure, using a heat pump significantly reduces the delivered energy demand compared to other technologies, such as direct electricity or biomass boilers.

Almost all packages are heavily dependent on electricity as seen by assessing the total delivered electricity demand (Figure 13). The exceptions were R 3.4 and R 4.4, which is expected as these packages included a biomass boiler covering 90% of the energy demand for space heating and domestic hot water.

5.1.2 Base Case assumptions

By examining Figure 10 it's evident that the initial assumptions for the Base Case will have influenced the results of the economic analysis. The assumption for the Base Case was to model the first two age cohorts as historically upgraded before new measures were applied. The energy demand for the oldest age cohort is significantly reduced in the Base Case compared to the buildings original state. The possible energy savings related to applying extra insulation will therefore also be reduced. This may influence the economic analysis, and packages that would have been beneficial for the original building envelope, may not become beneficial with the Base Case as the starting point. However, if a package is economically viable compared to Base Case, it is surely viable for buildings at their original state as well. Since only 9 % of buildings from the first cohort were at their original state according to (Mjønes et al., 2012), this assumption should yield a good result for the average single Family dwelling constructed before 1956.

The Base case assumption will also influence the result for buildings from the middle cohort, 1956 – 1970. The same implications described for the first cohort will hold for this as well.

The energy demand is reduced compared to its original state and thus the possible energy savings. In addition the Base Case energy demand for buildings in this cohort is lower than for the last cohort. It has the lowest base case energy demand. Therefore improving the building envelope, will result in lower energy reductions in this cohort, compared to the other two. As 20% of buildings belonging to this cohort still are at their original state, the BC assumption is likely to influence the economic analyses more for this age cohort, compared to the first one.

Part of the Base Case assumptions was to upgrade the windows as well. Even if they were upgraded to the worst U-value available these windows still induce an energy saving. As suggested by the results from the MSc Project, upgrading windows will give a significant reduction in energy use. Thus, the possible energy savings of upgrading to TEK 10 or Passive House standard is decreased with this assumption for the Base Case. This will probably have most influence on the economic analysis for packages such as R 1.0.1, R 1.0.2, R 2.0.1 and R 2.0.2 as they only focused on upgrading the façade and windows.

5.1.3 Additional insulation

The price of the insulation was found in Rockwools pricelist and was given for standard insulation thicknesses (Rockwool, 2014). This resulted in more insulation being applied in many cases, than strictly needed to reach the requirements of TEK 10 or Passive Houses. This was particularly the case with the first age cohort. Therefore upgrading the envelopes may not reduce the energy demand proportionally for all cohorts. As seen in Figure 11 the oldest buildings become the most energy efficient as larger parts of the envelope is rehabilitated. This is because the additional insulation needed was very large, and using the standard insulation thicknesses overestimated the insulation applied. In addition it can be seen from this figure that the last age cohort (1970 – 1980) has the highest energy demand as of package 3.0. This is because no extra insulation is applied to the floors, as this building cohort has no cellar basement. This result is in contrast to information from (Byggforsk, 2004a) where insulating floors were assessed to have little impact on the heat transmission of the building.

The rehabilitation packages were designed based on the Kyoto Pyramid, by first reducing the heat loss and thus the energy demand, before choosing a proper energy supply system. Figure 11 depict the net specific energy demand of the buildings. It may come as no surprise that the net energy demand decrease with the increasing thickness of the additional insulation. Furthermore, examining Figure 12 the most energy efficient solutions are those involving a heat pump and of course rehabilitation package 5.0 and 5.1 which will reach nearly zero energy demand over the year due to on-site production of electricity. It should be mentioned that these packages are only hypothetical as they require an electricity grid fit for exchange of electricity. This is not yet the case in Norway.

5.1.4 Managing the standard requirements

In order to reach the TEK 10 Energy Framework requirement a balanced ventilation system is needed (Table 18). This result matches the results from the MSc Project work. If a balanced ventilation system is installed all packages, which includes rehabilitation of the entire thermal envelope with TEK 10 components, will reach the Energy Framework requirement. This happens despite the fact that the thermal surcharge factor is held constant, and is in striking contrast to the results for Passive Houses. None of the packages designed to reach the Passive House level manage the energy requirement. This is mostly due to the thermal bridging surcharge as discussed in the next section.

5.1.5 Influence of the thermal bridging factor

The heat loss number was not sufficiently reduced in all cases for financial funding to be given. Only the 4 and 5 rehabilitation packages will receive funding, and only at level 2, explained in chapter 3.4.4. The thermal bridging factor ΔU_{thr} was probably set too high for this analysis, as explained in chapter 3.2.2. Considering Table 19 and Table 20 it's evident that the surcharge factor does have a significant influence on the results.

With a surcharge factor $\Delta U_{\text{thr}} = 0.10$ none of the Passive House rehabilitated buildings actually reach the Passive House standard regarding specific energy demand. Simulating the same building envelopes only changing the bridging factor to 0.03, which is the Passive House standard requirement, ensured that all Passive House rehabilitated buildings, belonging to the first two age cohorts, managed the energy requirement of the standard. The last age cohort does not include additional insulation of the floors, which may explain why this building doesn't manage the requirement.

A sensitivity analysis of Passive House rehabilitated buildings showed that decreasing ΔU_{thr} by 70%, in order to meet the Passive House requirement, decreased the energy demand by 40 – 50% for all building envelopes. Considering this is, but one amongst many factors influencing the energy balance of a building, it seems to be quite influential.

This proves that thermal bridges in the construction have a major influence on the buildings energy demand. Considering the information from (Hoberg, 2014), regarding the difficulty of calculating this factor, one can ask if the standard requirements are too ambitious. As the thermal bridges have such a large influence on the heat loss through the building and thus the energy demand, the assumption used in this work will have influenced which packages that may receive funding from Enova, and thus the economic analysis. This may also indicate the requirements for receiving such funding are too strict. Furthermore, it reflects that policy makers don't have a sufficient understanding of all the parameters influencing the energy balance of a building. Hopefully MSc Theses, such as that of Martin Hoberg, may give a better understanding of constructional thermal bridges, leading to better adjusted standards.

5.1.6 Comparison to literature

The results found in this research indicate that managing the energy target of 70kWh/m^2 as given by the Arnstad group is technically possible. For those packages including a Heat Pump managing this target seems very achievable, as seen in Figure 12. Especially the passive house rehabilitated envelopes (rehabilitation packages 4.0 – 5.1) are well within this limit. Energy demand for DHW, lighting and electrical appliances, have not been accounted for in Figure 12, meaning that the total delivered energy demand is higher. Keeping a total delivered energy demand at approximately the given limit should still be possible, considering only the technical aspects. If rehabilitated buildings are to achieve the stricter requirement of 30kWh/m^2 from 2040 and onwards, the results indicate that energy efficient DHW-systems, as well as more efficient lighting and electrical appliances, may be needed. Achieving a delivered energy demand of only 30kWh/m^2 should according to these results be possible, at least technically feasible. However, as stated by (Blight and Coley, 2013) the more energy efficient a building becomes, the more the occupants behavior will influence the energy demand.

The model doesn't consider energy demand for lighting and appliances and standard values must therefore be added to the results to establish total delivered energy demand. Considering information from (Risholt and Berker, 2013) indicating that the standard values may be higher than the corresponding real life values, there are large insecurities related to the total delivered energy demand. Hence, the focus has been placed on the specific delivered energy demand for space heating instead.

The energy balance model only consider operating energy, not accounting for embodied energy in building materials. Performing a life cycle assessment of the energy demand in buildings, including the embodied energy would give a more detailed picture. However, studies as those performed by (Sartori and Hestnes, 2007) and (Sandberg et al., 2011), indicate that the energy consumption in the dwelling stock is heavily dependent on the use phase. The decision of only include the operating energy, should therefore not affect the credibility of the results.

5.2 The Economic analysis

5.2.1 General discussion regarding the packages

The Base Case was assumed to be a state where some rehabilitations had to be carried out when the technical lifetime of the component in question came to its end. As all buildings are quite old, the base case automatically included upgrading of many components, and thus is related with a high cost.

The rehabilitation packages were meant to show the costs of rehabilitations giving an improved energy balance, compared to just keeping the building intact. Comparing Table 22 with Figure 18 it's evident that, for instance, the extra cost of better windows is small compared to the cost of changing windows in the first place. Thus, even if the economic analysis has not been carried out on a component level, it's evident that if rehabilitations such as changing windows or adding insulation on walls are to be carried out, the extra cost of more insulation or better windows, is marginal. However, by examining Figure 14 and Figure 15 it can be seen that only adding insulation and upgrading the windows will not be profitable compared to Base Case for the two first age cohorts (R1.0.1 and R1.0.2). When extra insulation is applied on the roof as well as façade and windows upgrading, the energy savings are great enough to make this option economic (see R 2.0.1 and R 2.0.2), with the exception of cohort 56 – 70. However, this can be the result of the assumptions for the base case described in the previous chapter.

The results on component level seems to agree with (Asplan Viak, 2012) where for instance upgrading windows were found to be cost effective even to the passive house level. Applying insulation on walls and roof were not found to be cost effective at TEK 10 level in contrast to this work. However, it should be noted that the current work doesn't investigate the costs on component level, and the results are therefore not directly comparable. However, the results clearly show that applying insulation to the level of Passive House is more beneficial, as indicated by Asplan Viak as well.

Balanced ventilation is not profitable for TEK 10 upgraded houses unless a heat pump is included (Figure 15). The additional cost compared to BC is small, and this may be due to wrong estimations of other costs in package R 3.1. During the cost gathering part of this project the price variation for the balanced ventilation system was found to be quite large. Therefore the results were found for two different prices, one provided by Norsk Prisbok, and one by Flexit ventilation systems. Comparing Figure 14 and Figure 15 reveal that the price of this component has implications for the results. Package R 3.2 is for instance not economic using the price from Norsk Prisbok, but it is when using Flexit systems. And even package R

4.3 has a very limited additional cost when using the price from Flexit systems. As this price was given based on information regarding the specific buildings used in this work, while the price from Norsk Prisbok is an average, most confidence is placed on the Flexit price. For the rest of the analysis the balanced ventilation was based on the cost given by Flexit Systems.

The air-to-air heat pumps are a good investment according to these results. As the Base Case is heavily dependent on electricity for space heating, this seems reasonable. The heat pump will decrease the electricity demand, and thus the energy related cost, by a substantial amount. As long as the heat pump isn't too expensive the investment is paid off by the energy related savings.

Installing an air-to-water heat pump does not come off as an optimal solution. Examining both Figure 14 and Figure 15 reveals that installing such a heat pump is neither economic in a TEK 10 upgraded nor a Passive House upgraded house. By looking at Figure 19 and Figure 20 it can be seen that this is due to the substantial cost of the waterborne space heating system. Furthermore rehab package R 3.3 is more expensive than R 4.3 and this is mainly due to the added cost of the space heating system. This is explained by the prices used for these systems. Norsk Prisbok states that a waterborne space heating system is less expensive when installed in a Passive House, most likely due to the lower heat demand in such houses. Thus the difference in additional cost of package R 4.3 and R 3.3 has two main reasons; the energy cost for case R 4.3 is smaller, as the energy demand is less compared to R 3.3 and the space heating system in case R 3.3 is more expensive. This is a possible error in the model as the cost of the space heating system in the Passive House may be underestimated. However, as none of the packages are economically viable compared to the Base Case it has no implications for the further results. These results are consistent with information provided by (Multiconsult, 2010) which indicated high costs related to waterborne space heating systems in Norway, and added costs when installing such systems in already existing buildings.

5.2.2 The best solutions

Based on these results rehabilitation to Passive House standard is the best option as long as financial funding is included (R 4.2). If funding is not included R 1.1.1 is the best solution, confer Figure 15 and Figure 16, and Table 59 in Appendix H. The most economical solution is package 4.0, which included rehabilitation to passive house level, without upgrading the ventilation or energy supply system. However, this solution is not feasible. More insulation will increase the need for ventilation as it leads to a tighter building envelope. Not installing a ventilation system puts the building at great risk for moisture damage. Additionally the Passive House standard clearly requires the building to be heated by more than direct electricity alone. Therefore the most economically viable solution, which also is feasible, is rehabilitation package 4.2, including balanced ventilation and an air-to-air heat pump. The Kyoto Pyramid stated that the greatest energy efficiency is achieved when reducing the heat demand first, before choosing suitable energy supply solutions. This economic analysis

revealed that this can also lead to the best solution in terms of economics. Although it should be mentioned that the analysis is subjected to many insecurities, affecting the robustness of the results.

5.2.3 Financial Funding

Financial funding seems to be important in order to make energy rehabilitations of economic interest for private homeowners. Comparing Figure 16 and Figure 15 show that for instance rehab package R 4.2 will not be economic for all age cohorts if no funding is available. Considering that the transformation of the dwelling stock is depending on the private homeowners' will to implement energy saving measures, it could be argued that the funding is too low. For instance, no funding is available for PV-panels. As long as the Norwegian electricity grid isn't fit for grid connected nZEnB exchanging electricity with the grid, this may not need funding. However, if it is desirable to increase the share of PV-panels in Norway, funding is needed to make this an option for private homeowners.

Looking at the results displayed in Figure 15 one can also ask why Enova has stopped the funding for pellets boilers. The packages including such a boiler are by far the most expensive. Considering that Norway has such cheap electricity and large amount of hydropower, it may not be of crucial importance to ensure that buildings become less dependent on electricity. In that regard the focus should be on reducing the heat loss associated with buildings along with a broader implementation of heat pumps reducing the electricity demand, instead of broad implementation of biomass boilers. Electricity is however, a high quality energy carrier, which should be used to cover activities needing high quality energy. Heating of buildings is not such an activity, and less electricity use in buildings will free more electricity for other purposes.

5.2.4 Sensitivity analysis of the electricity price

The sensitivity analysis showed that the packages are very dependent on the electricity price. By doubling the price all packages, except from package R 3.4, became economically viable, compared to the Base Case. This agrees with information from (Rambøll AS and Xrgia AS, 2011) where increasing electricity prices were found to increase both the technical and market potential. The Base Case is heavily dependent on electricity and therefore vulnerable to spikes in the electricity price. As can be seen from Figure 17 all packages including a heat pump became extremely beneficial, the best case would save up to 2000 NOK/m² compared to the Base Case.

More insight to which packages are most affected by the increase in electricity price is provided by examining Table 21. The electricity price was increased by 100% in year 2014 and held constant at this value throughout the period of analysis. In the first analysis the

electricity price was held constant throughout the entire period as well, meaning that the price was doubled for all years. As can be seen in this table the Base Case is most affected by this increase. A doubling of the electricity price induced 36 – 39% increase in the NPV of this case. Considering that the other packages only experienced an increase of 7% - 17% this explains why almost all the packages become economically efficient, with increased electricity prices. Furthermore the increase in NPV is significantly low in all packages including either a heat pump or a biomass boiler. This is reasonable, since both will decrease the demand for electricity significantly.

Furthermore according to the results only package R 3.4 will not become economically viable due to the increased electricity price. This has two main reasons. First the package includes a biomass boiler, meaning that the electricity demand is quite low to begin with, making it less dependent on the electricity price. Second the initial investment required in this package is quite large. The energy related savings are not large enough to offset this extensive investment.

As seen by Table 21 the NPV of the nearly zero-energy rehabilitations (R 5.0 and R 5.1) will not increase with increasing electricity price. As a matter of fact the NPV of R 5.0 will decrease with 2 – 3%. The assumption for these cases was that PV-production will counterbalance the entire energy demand, meaning both the electricity demand and the energy demand covered by biomass, as for in the case of R 5.0. Therefore, increasing the electricity price will result in a higher revenue on the electricity sold to the grid, compared to the combined cost of both electricity and biomass.

It's not very likely that the electricity price would suddenly spike as much as portrayed here. An increase of 100% in the electricity price over night will not happen. However, it is not unlikely that the electricity price will increase in the future. The more transmission lines being built between Norway and the European continent, the more Norway becomes dependent on the energy situation in Europe, especially in dry years, when national hydropower production isn't enough to cover the energy demand within the country. It could be interesting to examine how much the electricity price must increase before cases such as R 4.4 and R 5.0 become profitable. This could for instance be carried out in a model taking different electricity price scenarios into account.

Based on the economic analysis four rehabilitation packages were chosen to be investigated further in the scenario analysis. Rehabilitation packages R 1.1. and R 4.2 were chosen because they were profitable packages which will take the building to two different energy levels. In addition package R 4.4 and R 5.0 were chosen. Package R 4.4 is interesting because biomass is used to cover most of the heating demand and is related with a different emission intensity compared to the other packages, which mainly use electricity. As Package R 5.0 portrays a situation with nearly Zero Energy Buildings this package is also interesting for the scenario analysis, and was chosen regardless of its quite extensive additional costs.

5.2.5 The Payback time

The NPV analysis revealed which packages that would be most beneficial compared Base Case. The payback time was assessed to provide information on how long it takes before the investment is paid off by the benefits. As all the packages have been assessed relative to the Base Case scenario it was decided not to consider the total payback time, only the payback time relative to the base case. Thus this will not reflect the actual time it takes before the total investment is paid off. Instead it provides information about the additional investment cost of the packages compared to the Base Case, and how long it takes before this, additional cost, is paid back with the energy and maintenance savings. This information only provides an indication on how large the investment is compared to the related savings when implementing the rehabilitation package.

As can be seen from Table 23 rehabilitation package R 1.1.1 has a very short payback time, R 4.2 has a relatively long payback time and packages R 4.4 and R 5.0 will not be paid off during the period of analysis.

The most useful information the payback time provides is how likely it is to carry out these rehabilitations. Rehabilitation packages with short payback times will be relatively safe to invest in. All packages which are economically viable, will be good investments in monetary terms. However, the mere fact that a solution is profitable over a long time period, as in this work, does not ensure it's a good solution for a specific homeowner. If the homeowner only see himself living in the dwelling for 5 – 10 years it would not be profitable to invest in package R 4.2, even if it is economically viable over the period from 2014 to 2050. Considering that this analysis is carried out for single-family dwellings this may not be such an important factor. Such dwellings are quite expensive, and probably to a large extent bought by families intending to live there for more than 5 – 10 years. However this provides information on a variable not taken thoroughly into account in this work; how the occupancy behavior affects the private homeowners' will to implement energy rehabilitations in their homes.

5.3 The Future scenario model

5.3.1 The future development in the building stock

In contrast to most other studies, projecting the future development in the building stock, these calculations are based on probability distributions for the renovation and demolition lifetimes. As indicated in the literature, most studies assume fixed rates for the building stock. Consequentially most studies assume a linear increase in the dwelling stock. Figure 21 depicts the total stock increase from 1800 to 2050 as given by the Segmented Building Stock Model. The model show a non-linear increase in both the segmented and total building stock. Detached houses, for instance, experienced a rapid increase until present day, while the trend towards 2050 is a moderate increase before levelling off. Compact buildings, on the other hand, have a historically slow growth, with a rapid increase from ca. year 2000 onwards.

The current work is concerned exclusively with the development of the energy demand in today's standing stock of detached dwellings. New construction of buildings and their energy balance is beyond the scope of the project. However, it is interesting to note how the dwelling stock is likely to change over time, as well as the development of each segment. Considering that such a large part of the current stock comprise of detached dwellings, the renovation potential for this segment is perceived as large, in the coming decades.

Renovation lifetime profiles

When calculating the future energy and emission development, as well as possible savings a 40 year renovation lifetime with a deviation of 10 years was chosen. In addition the building stock was simulated for two other renovation lifetimes, in order to investigate how the renovation lifetime influences the development in the future dwelling stock.

Renovation lifetime of 20 years

Using a renovation lifetime of 20 years with a standard deviation of 5 years increase the number of dwellings that are renovated during the period. Renovations are carried out more frequently, thus increasing the renovation volume. As the current analysis only takes consideration the stock currently in place, and disregards all new constructions for the coming years, such a frequent renovation profile leads to the peculiar shape seen in Figure 25. The accumulated volume of renovated buildings will at some point, between 2034 and 2037, exceed the number of non-renovated buildings. As the number of renovated buildings obviously can't become negative the shape displayed in Figure 25, indicates that buildings are being renovated more than once.

The method for calculating the future energy and emissions, provided in the current work, isn't able to incorporate that a building is renovated more than once. This would require a stepwise reduction of energy demand for each of the renovation periods.

According to (Asplan Viak, 2012) a stepwise decrease of energy demand in the building stock by component requirements are probably the best way to ensure a decreasing energy demand in the stock. It could therefore be argued that using a shorter renovation lifetime combined with defining different energy reductions, for each renovation stage, may yield a more correct analysis of the future energy demand. However, the scope of the current project is not to decide upon the best solution, rather to show possible energy and emission developments. With this in mind using a short renovation lifetime seems to introduce more problems than benefits. In addition the renovation packages involve quite extensive rehabilitations and are therefore not assumed to be carried out frequently.

Renovation lifetime of 60 years

Assuming a longer renovation lifetime decreases the accumulated number of renovated dwellings in all age cohorts. Considering Figure 26 and Figure 27 it's evident that an increased renovation lifetime, has the largest influence on age cohort "> 1956". Considering the information that 25% of all single-family dwellings in 2011, were constructed before 1956, a long renovation lifetime will clearly eliminate the large energy efficiency potential in this part of the stock. In addition the buildings assessed are generally old, and probably need rehabilitations already. Hence, using a long renovation lifetime will probably not be suitable for this part of the dwelling stock.

Energy and emissions based on different scenarios

According to Table 30 its evident that different rehabilitation rates will influence the results. Using a renovation lifetime of 20 years will significantly increase the accumulate energy and emission savings compared to a renovation lifetime of 40 years. Nevertheless, based on the discussion in the previous sections, all in all assuming a renovation lifetime of 40 years, seems to be the best solution.

5.3.2 Future energy scenarios

As is to be expected the energy demand in the building stock will decrease if rehabilitations are implemented for all renovated buildings. Figure 28 displays the total energy demand for the current building stock, as it develops when different rehabilitation strategies are carried out on all renovated buildings. In addition the energy demand when no rehabilitations are carried out, is shown as well (C0). However it is unexpected that the future energy demand decrease in an almost linear fashion. Considering that the building stock development is based on a dynamic analysis, the development in the energy demand was expected to evolve in a more dynamic fashion. Considering Figure 36 (Appendix I) the energy development seems more dynamic when using a renovation lifetime of 60 years. Therefore the near linear decrease Figure 28, is assumed to be explained by the renovation profiles of the different age cohorts, rather by an error in the model. As seen by Figure 22 the renovation profiles are quite different, especially the first two age cohorts have profiles that may give linear results when they are combined. Figure 23 also show that when accumulating the stock all segments decrease almost linearly and the amount of renovated buildings increase in a near linear fashion.

Base Case included changing windows to a slightly better U-value and thus would induce a slight decrease in energy demand, compared to projecting the current energy situation. The energy demand decreases in C0 as well because buildings are being demolished. The accumulated energy demand of C1 is 3% lower than C0 as seen in Table 24. This suggests that the assumptions made for the BC, are not greatly influencing the calculated energy savings.

As seen by Figure 28 the energy demand decrease most rapidly when implementing package R 4.2 (C3) and R 5.0 (C4). Implementing rehabilitation packages R 1.1.1 and R 4.4 induce a nearly identical decrease in energy demand i.e. Figure 28. As package R 4.4 includes a larger reduction of the heat loss, in addition to a biomass boiler which most of both space heating and DHW, this indicates that an air-to-air heat pump reduces the energy demand quite extensively.

The accumulated energy analysis yield similar results as seen in Table 24. The accumulated energy saving potential of package R 1.1.1 and R 4.4 is similar, with 12% and 13% decrease compared to the BC scenario. Implementing package R 5.0 will induce 9% larger accumulated energy savings compared to package R 4.2. The accumulated saving of rehabilitation to nearly zero-energy buildings may be expected as much larger, compared to the corresponding savings when implementing R 4.2. However, these savings are calculated for the entire stock (not including new construction), while the energy savings are only found in the rehabilitated mass. Hence, these results indicate that the energy demand in the non-renovated part of the dwelling stock is quite large. If new constructions were included the difference of accumulated energy demand between the two packages (R4.2 and R 5.0) is expected to increase..

Package R 5.0 and R 4.4 (C4 and C5) respectively are both unlikely to be implemented. Neither was economically viable compared to the BC and both had a payback time beyond the period of analysis. Therefore installment of pellets boilers are seen as very unlikely on a large scale, and R4.4 has been shown in the scenario model only to evaluate the primary energy and emissions resulting from biomass use. Some people might be want to invest in PV-panels because of their environmental awareness. However, as the economic analysis indicate an extensive, additional cost related with this option, it's not likely to be implemented on a wide scale.

The given scenarios are not to be understood as the likely development, only as the possible development if the rehabilitation packages are implemented on a full scale. Developing more realistic scenario would involve further division of the rehabilitated building stock, depending on the level of rehabilitation likely to be carried out on each sub segment. This could only be achieved by predictions regarding the future likely rehabilitation effort, which would, to a large extent, depend on private homeowners' willingness to carry out such rehabilitations. As this, in the best case, would be the result of qualified guess work, such scenarios were defined as beyond the scope of this work.

Rambøll and Xargia estimated the technical energy saving potential to 5 TWh/ year in 2020 and 15 TWh/year in 2040. Table 60 in Appendix I gives an overview of the energy savings of each scenario compared to C1 (BC). The numbers are given both as the yearly and the accumulated savings. The highest saving is achieved with scenario C4 (implementation of R 5.0) and amounts to 2 TWh in 2020 and 6 TWh in 2040. As discussed in the preceding paragraph, full implementation of R 5.0 is very unlikely. Therefore it's more relevant to compare the literature to the energy savings achieved by scenario C3.

Full implementation of scenario C3 will result in a reduction of 0.2 - 1 TWh/year during 2014 – 2020 and 2 – 4 TWh/year between 2020 and 2040 (i.e. Table 60) . Considering that the energy savings are only related to a small part of the stock with all future construction disregarded, the results are not directly comparable to those of Rambøll and Xargia, or those found by Arnstad et al. The latter estimated possible savings of 10 TWh/ year in 2020, of which 8 TWh/year must be saved in the existing building stock. This seems like an ambitious target compared to the savings found in the current project. Even if these results only relates to a small part of the building stock, scenario C3 is ambitious in itself, since it assumes full implementation. It's not likely that all rehabilitated buildings will undergo such an extensive rehabilitation.

The dwelling stock model used for this analysis is also likely to give different results compared to other studies as probability distributions have been used for the demolition and renovation rate. More research is needed, taking into account the entire building stock, in addition to how occupancy behavior is likely to influence the level of rehabilitations carried out.

Primary energy

As discussed in chapter 2.4 defining system boundaries as well as allocation methods greatly influence the results of the calculated PEF. The PEFs chosen in the current work is based on different sources which in turn have calculated these based on different allocation methods. For instance the PEF used for Norwegian electricity mix is based on information from Adapt Consulting (Adapt Consulting AS, 2012). Similarly the PEF for the Nordic el.mix is based on information from (Värmeforsk, 2011) and was calculated as the total PEF including renewable energy, while the PEF for PV-production was based on information from (Gibon, 2014), and include only the non-renewable part. (Aalerud, 2012) argued that if energy efficiency is the main point of using primary energy factors, they should only reflect the non-renewable energy used. Including the renewable part would mean that renewable technology with low efficiency could get higher PEF's than fossil fuel based technologies. Therefore the PEF for solar technology was used. The author is aware that this gives results that are not directly comparable. Further investigation along with better definitions of PEF's are therefore called upon, and suggested as future work.

The primary energy analysis as displayed in Table 28 showed that buildings accomplishing the target of net zero-energy when only considering delivered energy, will not manage it when primary energy is taken into account. When calculating the primary energy demand the energy consumed by the building increases, as the PEF's associated with these energy carriers are larger than 1. On the other hand, the production by the PV-panels is attributed less significance as the corresponding PEF is lower than 1. Consequentially, to ensure a net-zero energy balance, more electricity must be produced by the PV – panels. This will favor renewable energy production as argued by (Aalerud, 2012).

The different electricity mixes are related with different PEFs. When using a Norwegian electricity mix the PV-produced electricity must be almost doubled to ensure a net zero-energy building. The corresponding increase when using Nordic or European electricity mix is 2.4 and almost 5 times the production when primary energy is not accounted for.

A sensitivity analysis revealed how influential the primary energy factor of electricity is. A 100% increase in the PEF for Norwegian electricity mix induced approximating 90% increases in the accumulated primary energy demand for all scenarios. The increase is substantial because Norwegian buildings are heavily dependent on electricity. The result underlines the importance of correct calculation of PEF's if primary energy is to be used.

The results indicate that primary energy accounting is complex and heavily depend on correctly defined primary energy factors. For instance if the PEF for a country's electricity mix is set too low the needed renewable energy production will be greatly underestimated, and similarly overestimated in the opposite case. This show that developing accurate primary energy factors which can be internationalized is of crucial importance if primary energy factors are to be widely implemented.

5.3.3 Future emission scenarios

Comparison with literature and reduction targets

Appendix I further presents results from the scenario analysis. Comparing the emissions calculated during this work (Table 61) to the emissions calculated by NVE in 2007 show a significantly larger emissions in the current work. While NVE considered the emissions from the total Norwegian building stock to as 1.6 Mton CO₂-eq. in 2007, the results from this work amounts to 1.4 Mton CO₂-eq in year 2013. Considering that the current work only concerns one part of the building mass these emissions are remarkable high. However, this is explained by the fact that NVE considered the emission intensity of electricity to be zero. As shown throughout this analysis Norwegian buildings are heavily dependent on electricity. Thus disregarding the emissions connected to using electricity will obviously render quite different, and significantly lower results, compared to the present study.

Similarly compared to the estimated reduction potential of 13 – 16 million tons as given by (Regjeringen.no, 2012), the accumulated reductions as given by Table 62 (Appendix I) are significantly high. Considering these results it is evident that not including the emission intensities of electricity and biomass will underestimate the emissions resulting from the building stock, and thus the reduction targets will be set too low.

Assessment of different electricity mixes

The accumulated emissions for the stock are depicted in Figure 30, for all scenarios (C1 – C5), for three different electricity mixes. As can be seen from this figure, the emissions resulting from using Norwegian electricity mix is extremely low compared to using the Nordic, or especially in the case of the European mix. This is due to the low emission factor attributed to the Norwegian electricity mix. As Norwegian electricity is largely based on hydropower, less emissions are related to the Norwegian building stock compared to other countries. However, given dry years or a rapid increase in energy consumption in the future, more electricity must be imported from other regions. In that case, the emission scenarios using Nordic electricity mix will be better suited to indicate future emissions. The European mix is mainly used in the current work as a worst case scenario, as well as indicate the difference in results when using different electricity mixes.

When basing the calculations on different electricity mixes the related emission savings, compared to BC, varies greatly. For instance, when using Norwegian electricity mix renovation scenario C5, which includes the use of a pellets boiler, will not induce an emission saving compared to C1. On the contrary the accumulated emissions are increased significantly, depicted as the negative emission saving in Figure 31. This is because the emission coefficient attributed to biomass includes the biogenic emissions. Thus it becomes

much higher than the corresponding emission factor for Norwegian electricity mix. Using European electricity mix on the other hand gives quite another picture. As seen by Figure 32 there's definitely an emission saving of scenario C5 compared to C1. Once again this indicates how sensitive the results are to the different electricity mixes.

The increased emissions related to using the Nordic and European electricity, can also be seen in Table 29, which shows the percentage increase of the accumulated CO₂-emissions using these mixes, compared to the Norwegian mix. The emissions related to C5 increase the least because the energy demand in the renovated buildings is mostly based on biomass. Thus the emissions resulting from these buildings are not as sensitive to changes in the electricity mix.

As discussed throughout the last paragraphs when calculating the emissions resulting from the Norwegian dwelling stock, the electricity mix is of crucial importance. This was also found by (Sandberg and Brattebø, 2012). (Graabak and Feilberg, 2011) provided different projections for the development of the European electricity mix. The results showed that many different scenarios are possible. Figure 33 show the accumulated emissions found in the current work, both using Norwegian, Nordic and European electricity mixes, as well as the future possible EU electricity mixes, as estimated by (Graabak and Feilberg, 2011). As seen by this figure, using the numbers from Graabak and Feilberg result in much lower emissions compared to the current EU mix. The Ultra Green scenario will give accumulated emissions on the same level as when using Nordic electricity mix.

As commented by (Sandberg and Brattebø, 2012) using Norwegian electricity mix will underestimate the future emissions, as it does not account for import of electricity from sources based on fossil fuel. On the other hand Nordic electricity mix will probably overestimate the emissions. Therefore the Norwegian emissions are likely to be somewhere in the middle of the results based on Norwegian and Nordic electricity mixes. However, if future energy consumption was to increase, more energy must be imported, and thus the emission scenario will move towards the ones portrayed using Nordic mix.

5.4 Factoring in occupancy behavior

As already described through the literature review given in chapter 2.7 occupancy behavior will influence the energy use in a building. Even if, as found by (Risholt and Berker, 2013), many homeowners are conscious about their energy use, to what level, and how they define energy saving, as well as desirable indoor climate, varies significantly.

Historically, the energy prices in Norway have been quite low, and thus the incentives for energy saving measures in buildings, as well. As electricity is quite cheap and the effects of climate changes are not really felt in Norway, many people will not consider energy saving an important aspect. Increasing awareness of both the environmental and economic benefit of such measures might increase the willingness to invest. In addition some will choose to install balanced ventilation for the added benefit of a better indoor air quality, while others will not care about this at all. Keeping in mind information from (Blight and Coley, 2013) indicating that the indoor set point temperature is of major importance for the energy use in dwellings, different occupants will lead to different energy use in otherwise similar households.

Seeing that every homeowner is different, it's very difficult to factor in their behavior, in an analysis such as the current one. Considering information in the literature review, this factor is normally not accounted for, precisely for this reason. The energy balance model did not take into account the occupancy behavior. The results from the energy balance will therefore be subjected to insecurities. The largest insecurity, given by the occupants' behavior, is the indoor temperature. It was held constant throughout the analysis, only differing slightly depending on age cohort, as a result of the information given by (Mjønes et al., 2012). The temperature used however, was not very high and it is therefore possible that the energy demand is underestimated.

As economics to a large extent guide peoples choices on a daily basis, the economic analysis performed is an attempt to account for occupancy behavior, when considering future energy scenarios. Many measures were found to be economically viable taking a long term perspective into account. Analyzing the payback time it was clear that even if the energy rehabilitation is economic over the time period, the payback time may be too long for the best option. According to (NVE, 2013) households require a short payback period and this will therefore affect the willingness to invest in such measures.

On general terms factoring in the behavior of the homeowners were found to be difficult and more research into this area is needed if real life projections for future energy and emission scenarios, regarding the Norwegian dwelling stock, are to be achieved.

5.5 Critiques of the methods and future work

5.5.1 The Energy balance model

The basis for the energy balance model has not been changed compared to the MSc Project work, even if the packages have been redefined. Thus the critiques given in the Project work is valid for the current work.

Thermal bridge surcharge was assessed as a significant uncertainty in the Project work and was thus kept constant during this work. In addition when upgrading the thermal envelope and installing ventilation system the air exchange rate was altered to meet the standard requirements.

The methodology used is based on TABULA, which is a standardized method to be used across borders. Thus the method may not be perfectly suited to assess the Norwegian dwelling stock. However, the results from the MSc Project indicated that the numbers calculated by the TABULA method didn't deviate significantly from those of other studies, and the method was therefore assessed as satisfactory.

Considering that all further calculations are based on the assumptions and calculations carried out for the energy balance model, these assumptions will have great influence on the result. Generally speaking the energy balance model includes many parameters, all which are based on different sources. Hence, these results must only be regarded as indicative for the Norwegian dwelling stock. For instance the domestic hot water demand is calculated based on standard values from NS 3031 along with efficiency losses of storage and distribution as given by (TABULA, 2013). Obviously basing the calculations on many, different literature sources, as well as a model not developed for Norwegian conditions, will result in numbers subjected to insecurities. To assess how all these different parameters influence the energy balance, a sensitivity analysis should be carried out for each one. However, this would constitute a Master Thesis in itself and has therefore not been carried out. Especially since the numbers calculated during the Project work indicated that the model yielded good results, it's been assumed for the current work that the model can be used without too much problems.

A sensitivity analysis was carried out for the thermal bridging surcharge value, as it was assessed as a large insecurity in the Project work. As given by the results and discussed in chapter 5.1.5 this factor alone significantly influence the energy balance. Future effort should therefore be given to investigate the different parameters thoroughly.

Furthermore, factoring in occupancy behavior in these calculations is very difficult and has thus, not been done. Therefore, when applying the energy balances obtained from this model in a scenario analysis, this analysis cannot take into account that different owners influence

the energy demand in the stock. More research into dwellers activities and their influence on the energy demand is thus called upon.

5.5.2 The Economic analysis

The Base Case was established taking into account a great deal of cost components and the costs associated with the Base Case were found to be quite extensive. Overestimating these costs will increase the number of rehabilitation packages becoming profitable. A sensitivity analysis should have been carried out on all cost components, in order to increase the knowledge on which components are most influential. This is suggested as further works.

Similarly to the Energy Balance model the economic analysis includes cost components from various sources. Hence, the results will be subjected to insecurities. The numbers from Norsk Prisbok seemed too high for the ventilation system, if this also holds for other components, as windows and so on, the results become less robust. Therefore better results would have been obtained if all costs were given by one or few commercial actors.

The lifetimes of different cost components are based on many sources as well. If these are underestimated the rehabilitation packages will become more expensive than might be the real case. Similarly to the costs, obtaining the lifetimes from a few sources, would yield better results.

A general critique of both the energy balance and the economic assessment is that basing such calculations entirely on literature may give poor results. Throughout the entire MSc Project and MSc Thesis work, obtaining information about all the components have been the biggest challenge. A more specific survey of the dwelling stock, with further subdivision of dwelling types, would provide a better basis for these calculations. However, this would also imply an enormous amount of information gathering and processing and may still not result in a sound representation of all Norwegian dwellings. An average dwelling would still be needed for these calculations, and obviously an average is just that; an average. Thus it will be subjected to insecurities when calculations are carried out on a large scale.

Future work

A model taking into account possible future electricity price scenarios is suggested as future works. Moreover a sensitivity analysis of all cost components and their implications for the energy saving potential should be carried out.

5.5.3 The Future scenario model

The scenario model analysis will be subjected to insecurities as it is based on both the Energy Balance Model and the Economic Analysis. In addition the assumptions for the Segmented Building Stock model will influence the results, both regarding energy demand and resulting emissions. As discussed in chapter 5.3.1 the renovation lifetime will influence the results. Therefore using a fixed rate based on historical numbers, when projecting future renovations, will result in less robust numbers. Whether or not, using the rates suggested by Sandberg et al., is a better solution this analysis cannot decide. However, the model by Sandberg et al. is based on a long term study, considering different features of the Norwegian dwelling stock, thus it's assumed that it provides a better basis compared to using fixed rates.

The Segmented Building Stock model was found to be insufficient at one point. When using a short renovation lifetime buildings will be renovated more than once. However, the model doesn't provide the number of buildings being renovated for the second or third time. Thus if the model is to be used as it has been during this work, using a shorter renovation lifetime when estimating the energy demand, becomes difficult.

Sartori et al, considered that habits need time to change, and therefore used a transition period for the implementation of energy rehabilitations (Sartori et al., 2009). The current model doesn't take this into account, and the energy efficiency measures are all carried out in the year the building is renovated. As a scenario model is used for the renovation of buildings, the lack of a transition period may not be influential. However some buildings will be renovated in year 2014, and it could be argued that such a transition period should have been used. However, this would require yet another parameter subjected to insecurities. In an analysis such as the current one, with much insecurity already in place, it's of the author's opinion, that such a transition period would not have increased the robustness of the results in any. However, better understanding of occupancy behavior would increase the robustness. More research into how occupant behavior influences energy development is needed

Assessing primary energy showed that accounting for primary energy substantially increases the energy demand. In addition choosing the primary energy factors is complex, and more focus should be given to establishing these factors. The sensitivity analysis for Norwegian electricity mix further emphasized that correctly determining these factors, is of crucial importance, especially if policy decisions are to be made based on Primary Energy Assessment. Hence, further research is needed.

Future emissions are heavily dependent on the future electricity mix. Based on these results not implementing energy efficiency measures in the Norwegian dwelling stock may have negative, future consequences. These results have shown how dirty the electricity in Europe is, compared to Norwegian electricity. The more electricity saved in Norway, the more can be exported to the European market substituting some of the dirty electricity, inducing a positive effect on the total emissions.

6 Conclusion

The energy balance carried out, provided information about how different rehabilitation packages alter the buildings energy demand. Reducing the energy demand significantly is technically achievable. Approaching nZEnB by using a PV-panel is also manageable with current technology. However, managing Passive House level proved difficult if a realistic thermal bridge surcharge factor is used. If the factor equal the standard requirement, rehabilitation to a Passive House is achievable. Considering information suggesting that obtaining this factor is quite difficult, it's not seen as realistic to fully manage the Passive House requirement, when rehabilitating old single-family dwellings. Furthermore, according to the sensitivity analysis, this factor has large implications for a buildings energy consumption. Therefore more research into how this factor changes with rehabilitation, is needed.

Based on the economic assessment air-to-air heat pumps were found to be very cost effective. Considering that Norwegian dwellings are heavily dependent on electricity, all measures which significantly reduce the electricity demand will most likely be cost effective. In fact, the current dwelling stock is dependent on electricity to such an extent, that doubling the electricity price increases the NPV of Base Case with approximately 40%. Thus, if a large enduring increase in the electricity price was to happen, all but one package, would become profitable compared to Base Case. Furthermore these results indicate that those energy saving measures which greatly influence the electricity bill will be preferred by private homeowners. Moreover, the results indicated that if rehabilitations need to be carried out, using the most energy efficient components will be profitable. Furthermore, financial funding is needed to make extensive rehabilitations profitable. In fact the analysis found that more funding is needed, especially in order to make biomass boilers profitable.

Different renovation lifetimes were found to influence the amount of renovated buildings, and thus the possible energy and emission savings, greatly. Therefore choosing a constant renovation rate, as done by other studies, will probably have influenced those results significantly. As the current work takes into account emission intensities for electricity and biomass combustion, the resulting emissions from the dwelling stock is large, compared to other studies. This indicates that disregarding these emissions, will have major implications on projected emission reductions for this sector. Furthermore, the scenario analysis revealed that the electricity mix is of crucial importance when calculating future emissions. Norwegian dwellings are heavily dependent on electricity, and future emission saving potentials greatly depend on the amount of electricity being imported to Norway. In conclusion rehabilitation strategies will decrease the energy demand and associated emissions. However, the energy demand depends on other factors as well, such as the renovation lifetime, energy and emissions factors, electricity mixes, and occupancy behavior.

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Appendix A Norwegian building standards and technical regulations

The Technical Regulation, TEK 10 (TEK10, 2010)

Table 32: Energy requirements of TEK 10

§14-3 Energy requirements	
1. Total area of windows and doors	$\leq 20\%$ of heated part of BRA
2. U-value envelope wall	≤ 0.18 [W/(m ² K)]
3. U-value roof	≤ 0.13 [W/(m ² K)]
4. U-value floor	≤ 0.15 [W/(m ² K)]
5. U-value windows/doors	≤ 1.2 [W/(m ² K)]
6. Normalized thermal bridging value for detached dwellings	≤ 0.03 [W/(m ² K)]
1. Infiltration at 50 Pa pressure difference for detached dwellings	≤ 2.5 [1/h]
2. Yearly average temperature efficiency of ventilation heat recovery for detached dwellings	$\geq 70\%$
1. Specific Fan Power for ventilation system in detached dwellings	≤ 2.5 [kW/(m ³ /s)]
c) Further requirements	2. A possibility for night- and week-end set back of indoor temperature. 3. Measures to reduce the buildings need for local cooling.

Table 33: The Energy Framework requirements of TEK 10

§ 14-4 Energy Framework requirement for detached dwelling	
Total net energy need (based on NS 3031)	$120 + 1600/(\text{Floor area})$ [kWh/m ² heated BRA per year]

Table 34: Minimum technical requirements for detached dwellings, TEK 10

§14-5 Minimum Requirements for detached dwellings	
U-value envelope wall	≤ 0.22 [W/(m ² K)]
U-value roof	≤ 0.18 [W/(m ² K)]
U-value floor against ground or air	≤ 0.18 [W/(m ² K)]
U-value window/door	≤ 1.6 [W/(m ² K)]
Infiltration at 50 Pa pressure difference	≤ 3.0 [1/h]

The Norwegian Standard NS 3031(Norsk Standard, 2011)

- BRA – utility floor space
 - Defined as the gross floor space minus the area of the walls
 - Heated area, A_{fl} is defined as the part of BRA that receives heat from the buildings heating system and which is enclosed by the buildings thermal envelope.
 - For areas that are unheated or only partly heated the heated area is determined as follows:
 - If the area is included in BRA the room is calculated as if it has the same temperature as the adjacent room
 - If the area is not included in BRA the rooms thermal resistance can be included when calculated the heat loss through building elements bordering on the unheated space.²⁷
- There are three calculation methods that can be chosen for calculating the heating- and cooling need, where only the two first ones are relevant for dwellings²⁸.
 - Stationary monthly calculations
 - Simplified time based calculation, dynamic method
 - Detailed validated calculation method, dynamic method
- The standard gives definitions on how to calculate energy need for space heating, energy need for space cooling, total net energy need, total delivered energy demand as well as primary energy need and CO₂-emissions.

Table 35: Energy demand for lighting, technical appliances and hot water.

Building type	Lighting appliances		Technical equipment		Domestic hot water		Min. specific airflow
	W/m ²	kWh/(m ² ·year)	W/m ²	kWh/(m ² ·year)	W/m ²	kWh/(m ² ·year)	
Detached dwellings ²⁹	1.95	11.4	3.00	17.5	5.1	29.8	1.2

Calculation of energy demand for the building:

Net energy need for space heating is found as the heat loss through transmission – the heat gain from ventilation. See NS 3031, chapter 6.1 for more information.

$$Q_{H,nd,i} = Q_{H,ls} - \eta_{H,i} Q_{gn,i}$$

Where

$Q_{H,nd,i}$ is the net energy need for space heating

²⁷ 4.2 NS 3031

²⁸ 4.4 NS 3031

²⁹ Detached dwellings are defined as single-family dwellings, multi-family dwellings and row-houses.

$Q_{H,ls,i}$	is the heat loss both due to ventilation and heat transmission
$\eta_{H,i}$	is the gain utilisation factor
$Q_{gn,i}$	is the solar and internal heat gain

When calculating $Q_{H,ls,i}$ the heat recovery of ventilation air is accounted for if heat recovery is used as described in chapter 6.1.1.1 and 6.1.1.1.4 in NS 3031. Heat received from the DHW-system is assumed to be zero as described in Tabell A.2 “MERKNAD 3” in NS 3031.

The total net energy need is calculated as the sum of energy need for space heating and cooling, energy need for DHW, energy need for pumps and fans, technical appliances and lighting, in addition to the heat needed to protect the heat recovery from freezing over. This is described in chapter 6.2 in NS 3031

The total delivered energy takes the system efficiency into account and is described in chapter 7.2 in NS 3031.

The Norwegian Standard NS 3700(Norsk Standard, 2013)

- Maximum heat loss by transmission and infiltration³⁰
 - Dwelling with $A_{fl} < 100 \text{ m}^2$, $H''_{tr,inf} \leq 0.53 \text{ [W/m}^2\text{K]}$
 - Dwelling with $100 \text{ m}^2 < A_{fl} < 250 \text{ m}^2$, $H''_{tr,inf} \leq 0.48 \text{ [W/m}^2\text{K]}$
 - Dwelling with $A_{fl} \geq 250 \text{ m}^2$, $H''_{tr,inf} \leq 0.43 \text{ [W/m}^2\text{K]}$

Maximum net energy need for space heating, depending on climatic conditions

Table 36: Passive House requirement maximum calculated net energy need for space heating

Average external temperature during the year θ_{ym}	Maximum calculated net energy need for space heating [kWh/(m ² ·year)]	
	Dwelling where $A_{fl} < 250 \text{ m}^2$	Dwelling where $A_{fl} \geq 250 \text{ m}^2$
$\geq 6.3 \text{ }^{\circ}\text{C}$	$15 + 5.4 \times \frac{(250 - A_{fl})}{100}$	15
$< 6.3 \text{ }^{\circ}\text{C}$	$15 + 5.4 \times \frac{(250 - A_{fl})}{100} + \left(2.1 + 0.59 \times \frac{(250 - A_{fl})}{100}\right) \times (6.3 - \theta_{ym})$	$15 + 2.1 \times (6.3 - \theta_{ym})$

³⁰ A_{fl} is the heated part of the BRA

θ_{ym} shall be calculated in Accordance with NS-EN ISO 15927 – 1:2003 as the mean temperature over the year, based on mean temperatures calculated for each day.

Calculation of the net energy demand for building before evaluation against the standard shall be based on NS 3031. Internal heat gains and air usage should be found in NS 3031 Table A.6.

- The building shall be constructed in such a way that thermal comfort can be achieved without cooling.
- The heating demand should be covered to a large extent by other energy carriers than electricity or fossil fuels. Calculated delivered electricity and fossil energy shall be less than total net energy need minus 50 % of net energy demand for hot water.

Table 37: Minimum requirement of NS 3700, for Passive House

Attribute	Passive House
U-value windows and doors	$\leq 0.80 \text{ [W/m}^2\text{K]}$
Normalized thermal bridging value Ψ''	$\leq 0.03 \text{ [W/m}^2\text{K]}$
Average temperature efficiency for heat recover system	$\geq 80\%$
SFP for the ventilation	$\leq 1.5 \text{ [kW/(m}^3\text{/s)]}$
Leakage rate at 50 Pa, n_{50}	$\leq 0.60 \text{ h}^{-1}$

Table 38: Typical U-values for Passive Houses

Building element	U-value Passive House $[\text{W}/(\text{m}^2\text{K})]$
Wall	0.10 – 0.12
Roof	0.08 – 0.09
Floor	0.08

Table 39: Energy demand for lighting, technical appliances and hot water.

Building type	Lighting appliances		Technical equipment		Domestic hot water		Min. specific airflow
	W/m^2	$\text{kWh}/(\text{m}^2 \cdot \text{year})$	W/m^2	$\text{kWh}/(\text{m}^2 \cdot \text{year})$	W/m^2	$\text{kWh}/(\text{m}^2 \cdot \text{year})$	
Detached dwellings ³¹	1.95	11.4	3.00	17.5	5.1	29.8	1.2

³¹ Detached dwellings are defined as single-family dwellings, multi-family dwellings and row-houses.

Appendix B The TABULA abbreviations

Table 40: The TABULA Abbreviations for all parameters used (Loga and Diefenbach, 2013)

Quantity	Explanation	Unit
$a_{H,0}$	constant parameter standard value for the seasonal method: $a_{H,0} = 0.8$ (according to EN 13790)	[-]
$\alpha_{nd,h,i}$	fraction of heat generator i used for space heating	[-]
$\alpha_{nd,w,i}$	fraction of DHW heat generator i	[-]
ΔU_{tbr}	surcharge on all U-values, taking into account the additional losses caused by thermal bridging	[W/(m ² K)]
$\eta_{h,gn}$	dimensionless gain utilization factor	[-]
ϕ_{int}	average thermal output of internal heat sources	[W/m ²]
$\eta_{h,gn}$	dimensionless gain utilization factor,	[-]
$\eta_{ve,rec}$	efficiency of ventilation heat recovery (weighted average during heating season)	[-]
$\vartheta_{e,b}$	heating base temperature	[°C]
$\overline{\vartheta_{e,hs}}$	temperature of the external environment (average value during heating season)	[°C]
$\overline{\vartheta_{e,i}}$	temperature of the external environment, average value for the respective day i	[°C]
ϑ_{int}	internal temperature (set-point temperature for space heating)	[°C]
τ	time constant of the building (see below)	[h]
$\tau_{H,0}$	is a constant parameter standard value for the seasonal method: $\tau_{H,0} = 30$ h (according to EN 13790)	[h]
$\tau_{H,0}$	is a constant parameter standard value for the seasonal method: $\tau_{H,0} = 30$ h (according to EN 13790)	[h]
$A_{C,extdim}$	conditioned floor area based on external dimensions	[m ²]
$A_{C,intdim}$	conditioned floor area based on internal dimensions	[m ²]
$A_{C,living}$	conditioned living area	[m ²]
$A_{C,ref}$	reference area of the building	[m ²]
$A_{C,use}$	conditioned useful floor area	[m ²]
$A_{window,j}$	area of all windows with orientation j	[m ²]
b_{tr}	adjustment factor soil	[-]

c_h, c_w	annual energy costs for space heating and domestic hot water	[€/m ² a]
c_m	internal heat capacity per m ² reference area	[Wh/m ² K]
$c_{p,air}$	volume-specific heat capacity of air	[Wh/(m ³ K)]
d_{hs}	length of the heating season expressed in days	[d/a]
d_i	duration of day i = 1 d i index of the days of a year	[d]
$e_{g,h,i}$	heat generation expenditure factor of heat generator i used for space heating	[-]
$e_{g,w,i}$	heat generation expenditure factor of DHW heat generator i	[-]
$A_{env,i}$	area of envelope element i	[m ²]
$f_{adapt,k}(q_{del})$	adaptation factor of type k, as a function of the delivered energy q_{del} (sum of energywares without auxiliary electricity) determined by standard calculation method	[-]
$f_{co2,aux}$	carbon dioxide emission factor of electricity used for auxiliary devices	[g/kWh]
$f_{co2,h,i}$ $f_{co2,w,j}$	carbon dioxide emission factors of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[g/kWh]
F_F	frame are fraction of the windows	[-]
F_{nu}	dimensionless correction factor for non-uniform heating, taking into account systematic deviations of the set-point temperature and the actual average temperature (time average over night and day as well as space average over living areas and reduced or indirectly heated spaces)	[-]
$f_{p,nonren,aux}$	non-renewable primary energy factor of electricity used for auxiliary devices	[-]
$f_{p,nonren,h,i}$ $f_{p,nonren,w,j}$	non-renewable primary energy factors of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[-]
$f_{p,total,aux}$	total primary energy factor of electricity used for auxiliary devices	[-]
$f_{p,total,h,i}$ $f_{p,total,w,j}$	total primary energy factors of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[-]
F_{sh}	reduction factor external shading	[-]
F_W	is a reduction factor, considering radiation non-perpendicular to the glazing	[-]
$g_{gl,n}$	total solar energy transmittance for radiation perpendicular to the glazing	[-]

$h_{room,ve\ ref}$	ventilation reference room height	[m]
H_{tr}	overall heat transfer coefficient by transmission	[W/K]
h_{tr}	heat transfer coefficient by transmission per m ² reference floor area	[W/(m ² K)]
h_A, h_B	are constants, depending on the building type	[W/(m ² K)]
H_{ve}	total heat transfer by ventilation	[W/K]
$I_{Sol,j}$	average global irradiation on surfaces with orientation j during the heating season	[m ²]
$I_{sol,k,hs}$	global solar radiation on 1 m ² surface of orientation k during the heating season	[kWh/(m ² a)]
$I_{sol,k,i}$	global solar radiation on 1 m ² surface of orientation k during day i	[kWh/(m ² d)]
k	orientation of a transparent surface	[-]
$m_{co2,h}$ $m_{co2,w}$	annual carbon dioxide emissions for space heating and domestic hot water	[kg/a]
$n_{air,infiltr}$	air change rate by infiltration	[1/h]
$n_{air,use}$	average air change rate during heating season, related to the utilisation of the building	[1/h]
p_{aux}	price of electricity used for auxiliary devices	[€/kWh]
$p_{h,i}$ $p_{w,j}$	prices of the energyware used by heat generator i of the heating system and by heat generator j of the hot water system	[€/kWh]
$q_{del,h,adapt,i}$ $q_{del,w,adapt,j}$	expectation value of the measured consumption for space heating and DHW	[kWh/(m ² a)]
$q_{del,h,adapt,i}$ $q_{del,w,adapt,j}$	annual energy use of heat generator i of the heating system and of heat generator j of the hot water system per m ² reference floor area, adapted to the typical level of measured consumption	[kWh/(m ² a)]
$q_{del,h,aux}$ $q_{del,w,aux}$	annual auxiliary energy use of heat generator i of the heating system and of heat generator j of the hot water system per m ² reference floor area	[kWh/(m ² a)]
$q_{del,h,i}$ $q_{del,w,j}$	annual energy use (delivered energy) of heat generator i of the heating system and of heat generator j of the hot water system per m ² reference floor area, calculated by applying the standard boundary conditions	[kWh/(m ² a)]
$q_{d,h}$	annual effective heat loss of the space heating distribution system per m ² reference floor area	[kWh/(m ² a)]
$q_{d,w}$	annual heat loss of the DHW distribution system per m ² reference floor area	[kWh/(m ² a)]
$q_{d,w,h}$	recoverable heat loss of the DHW distribution system per m ² reference floor area	[kWh/(m ² a)]

$q_{g,h,out}$	heat output of heat generator i used for space heating	[kWh/(m ² a)]
$q_{g,w,h}$	recoverable heat loss of the DHW heat generators per m ² reference floor area	[kWh/(m ² a)]
$q_{g,w,out}$	heat output of DHW heat generator i	[kWh/(m ² a)]
$Q_{H,gn}$	total heat gains for the heating mode	[kWh/a]
$Q_{H,nd}$	building energy need for heating, assumed to be greater than or equal to 0	[kWh/a]
Q_{ht}	total heat transfer for the heating mode	[kWh/a]
$Q_{ht,tr}$	total heat transfer by transmission during the heating season	[kWh/a]
$Q_{ht,ve}$	total heat transfer by ventilation during the heating season	[kWh/a]
$q_{ht,ve}$	annual heat transfer by ventilation per m ² reference floor area	[kWh/(m ² a)]
$q_{nd,h}$	annual energy need for heating (useful heat) per m ² reference floor area	[kWh/(m ² a)]
$q_{nd,w}$	annual energy need for domestic hot water (useful heat) per m ² reference floor area	[kWh/(m ² a)]
$q_{p,nonren,h}$ $q_{p,nonren,w}$	non-renewable primary energy demand for heating and hot water	
$q_{p,total,h}$ $q_{p,total,w}$	total primary energy demand for heating and hot water	[kWh/(m ² a)]
$q_{s,h}$	annual effective heat loss of the heating system storage per m ² reference floor area	[kWh/(m ² a)]
$q_{s,w}$	annual heat loss of the DHW storages per m ² reference floor area	[kWh/(m ² a)]
$q_{s,w,h}$	recoverable heat loss of the DHW storages per m ² reference floor area	[kWh/(m ² a)]
$q_{w,h}$	recoverable heat loss of the DHW system per m ² reference floor area	[kWh/(m ² a)]
$q_{ve,h,rec}$	space heating contribution of the ventilation heat recovery unit per m ² reference floor area	[kWh/(m ² a)]
$R_{0,i}$	thermal resistance of the envelope element i in the original state, calculated according to EN ISO 6946	[m ² K/W]
$R_{add,i}$	additional thermal resistance due to unheated space bordering at the construction element i	[m ² K/W]
$R_{eff,i}$	effective thermal resistance of the envelope element i	[m ² K/W]
$R_{measure,i}$	(additional) thermal resistance of a thermal refurbishment measure applied to the element i in case of a simple insulation measure (additional layer of	[m ² K/W]

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

Appendix C Equations for Energy balance

In this appendix all equations used to calculate the energy balance are presented. They are all based on the equations given in the TABULA method(Loga and Diefenbach, 2013)

Energy need for space heating: $Q_{H,nd} = Q_{ht,ve} + Q_{ht,tr} - \eta_{h,gn} \cdot (Q_{sol} + Q_{int})$

Heat loss/gain due to heat generators for space heating:

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

Heat loss/gain due to heat generators for DHW: $Q_{g,w} = Q_{del,w} - Q_{nd,w} - Q_{s,w} - Q_{d,w}$

Gain utilization factor for heating:

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

Solar heat load during heating season:

$$Q_{sol} = F_{sh} \cdot (1 - F_F) \cdot F_W \cdot g_{gl,n} \cdot (A_{window,hor} \cdot I_{sol_hor} + A_{window,east} \cdot I_{sol_east} + A_{window,west} \cdot I_{sol_west} + A_{window,north} \cdot I_{sol_north} + A_{window,south} \cdot I_{sol_south})$$

Internal heat gains during heating season: $Q_{int} = t_{dogn} \cdot \phi_{int} \cdot d_{hs} \cdot A_{C,ref}$

Heat transfer by ventilation during heating season:

$$Q_{ht,ve} = 0.024 \text{ kh/day} \cdot H_{ve} \cdot F_{nu} \cdot (u_{int} - u_e) \cdot d_{hs}$$

Heat transfer by transmission during heating season:

$$Q_{ht,tr} = 0.024 \text{ kh/day} \cdot H_{tr} \cdot F_{nu} \cdot (u_{int} - u_e) \cdot d_{hs}$$

Energy use for heat generator 1 of the heating system:

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

Energy use for heat generator 2 of the heating system:

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

Energy use for heat generator 3 of the heating system:

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

Energy use for all the heat generators of the heating system: $Q_{del,h} = Q_{del,h,1} + Q_{del,h,2} + Q_{del,h,3}$

The space heating contribution of the ventilation heat: $Q_{ve,h,rec} = \eta_{ve,rec} \cdot Q_{ht,ve}$

Recoverable heat loss from the DHW system: $Q_{w,h} = (q_{g,w,h} + q_{s,w,h} + q_{d,w,h}) \cdot A_{C,ref}$

Annual effective heat loss from the heating system storage: $Q_{s,h} = q_{s,h} \cdot A_{C,ref}$

Annual effective heat loss of the space heating distribution: $Q_{d,h} = q_{d,h} \cdot A_{C,ref}$

Energy use for domestic hot water heat generator 1:

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

Energy use for domestic hot water heat generator 2:

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

Energy use for domestic hot water heat generator 3:

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

Energy use for all the domestic hot water heat generators: $Q_{del,w} = Q_{del,w,1} + Q_{del,w,2} + Q_{del,w,3}$

Annual energy need for domestic hot water: $Q_{nd,w} = q_{nd,w} \cdot A_{C,ref}$

Annual heat loss from the DHW storage: $Q_{s,w} = q_{s,w} \cdot A_{C,ref}$

Annual heat loss from the DHW distribution: $Q_{d,w} = q_{d,w} \cdot A_{C.ref}$

Appendix D Assumptions and further results from the MSc Project

Assumptions

During the project work many assumptions had to be made in order to develop the typical dwellings, the most important ones are summarized in the following section.

1. Windows/doors: The u-values for the original buildings were set according to the report by Enova, although it can be debated that they are too low compared to other sources. The U-value was lowered for eah rehabilitation package, as seen in Table 41.
2. Floor- and roof area: The floor used was based on the report by Enova. The roof area was set equal to the floor area because the u-values used for the roof was calculated as effective u-values, accounting for cold attics, by Enova, and was thus interpreted as the area of the ceiling.
3. The indoor temperature for each age cohort was taken directly from the Enova report, and was an average of the temperature in the heated and unheated area of the buildings.
4. Thermal bridges: The TABULA methodology provides a factor accounting for thermal bridges, classified in four categories refering to the effect of the contructional thermal bridging. This factor was reduced when the building envelope was rehabilitated.
5. Air use and infiltration: The air use for each building cohort was based on the numbers given by Enova. The numbers was interpreted as the air-change rate per hour, as Enova failed to give the denomination of the air use. This values was not chaged when the building envelope was rehabilitated. The infiltration rate, however was decreased when rehabilitation measures were applied.
6. Climate zones: The energy balance model was applied for buildings modeled in 9 different climate zones, including one which was the average of the average of the Norwegian climate, to account for the very varying conditions in the country.
7. Energy carriers for space heating and domestic hot water: For all age cohorts the dwellings were assumed to use direct electricity in combination with wood fired stoves for space heating, and direct electricity for domestic hot water generation. These assumptions were based on an extensive literature search. The energy carriers were not assumed to change with TEK 10 and Passive House rehabilitation even if it is arequirement of both standards that the delivered energy is based on more than direct electricity or fossil fuel. The model required values related to the distribution and storage of hot water, and these were based on german values from the TABULA project (TABULA, 2013).

Table 41: U-values of the components used in the MSc Project thesis

<u>U-values on construction elements</u>			
	<u>>1956</u>	<u>1956 - 1970</u>	<u>1971 - 1980</u>
External walls			
Original envelope	0.96	0.5	0.41
Historically rehabilitated envelope	0.39	0.33	0.29
TEK 10 Enova rehabilitated envelope	0.19	0.19	0.19
TEK 10 Energy Framework requirement	0.18	0.18	0.18
Passive House std. rehab. envelope	0.11	0.11	0.11
Roof			
Original envelope	0.81	0.33	0.2
Historically rehabilitated envelope	0.31	0.2	0.16
TEK 10 rehabilitated envelope	0.15	0.16	0.16
TEK 10 Energy Framework requirement	0.13	0.13	0.13
Passive House std. rehab. envelope	0.085	0.085	0.085
Floor			
Original	0.61	0.28	0.36
Historisk oppgradering	0.27	0.18	0.36
TEK 10 oppgradering	0.14	0.16	0.15
TEK 10 Energy Framework requirement	0.15	0.15	0.15
Passive House standard upgrading	0.08	0.08	0.08
Windows			
Original	2.6	2.6	2.6
Historisk oppgradering	1.9	1.5	2.6
TEK 10 oppgradering	1.2	1.2	1.2
TEK 10 Energy Framework requirement	1.2	1.2	1.2
Passive House standard upgrading	0.8	0.8	0.8
Doors			
Original	2.5	2.5	2
Historisk oppgradering	1.9	1.5	2
TEK 10 oppgradering	1.2	1.2	1.2
TEK 10 Energy Framework requirement	1.2	1.2	1.2
Passive House standard upgrading	0.8	0.8	0.8
Thermal bridging ΔU_{tbr}			
Original	0.1	0.1	0.1
Historisk oppgradering	0.05	0.05	0.05
TEK 10 oppgradering	0.03	0.03	0.03
TEK 10 Energy Framework requirement	0.03	0.03	0.03
Passive House standard upgrading	0.03	0.03	0.03

Summary of changing parameters and the sources:

In the following table all parameters that are changed during the calculations are summarized together with the sources values have been based on.

Table 42: Summary of all changing parameters used for the MSc Project Energy Balance

<u>Parameter</u>	<u>Description</u>	<u>Source</u>
$A_{C,ref}$	Reference area	(Mjønes et al., 2012)
$A_{window.hor}$	Area of all windows with horizontal orientation	
$A_{window.east}$	Area of all windows with orientation east	
$A_{window.west}$	Area of all windows with orientation west	
$A_{window.north}$	Area of all windows with orientation north	
$A_{window.south}$	Area of all windows with orientation south	

$A_{env,wall}$	Area of envelope area wall	
$A_{env>window}$	Area of envelope area window	
$A_{env,floor}$	Area of envelope area floor	
$A_{env,door}$	Area of envelope area door	
$A_{env,roof}$	Area of envelope area roof	
$\alpha_{nd,h,1}$	Fraction of heat generator 1 for space heating system	<u>Space Heating</u> Heat generator 1: Electricity = 0.9 Heat generator 2: Wood = 0.1 <u>DHW</u> Heat generator 1: Electricity = 1 The rest = 0 (Storvolleng, 2013)
$\alpha_{nd,h,2}$	Fraction of heat generator 2 for space heating system	
$\alpha_{nd,h,3}$	Fraction of heat generator 3 for space heating system	
$\alpha_{nd,w,1}$	Fraction of heat generator 1 for domestic hot water system	
$\alpha_{nd,w,2}$	Fraction of heat generator 2 for domestic hot water system	
$\alpha_{nd,w,3}$	Fraction of heat generator 3 for domestic hot water system	
d_{hs}	Length of the heating season	(Olseth and Skartveit, 1987) and (Norsk Standard, 2011)
$e_{g,h,1}$	Heat generation expenditure factor of heat generator 1 for space heating system	Direct electricity, value from (Loga and Diefenbach, 2013)
$e_{g,h,2}$	Heat generation expenditure factor of heat generator 2 for space heating system	Wood as energy source (Pettersen et al., 2005)
$e_{g,h,3}$	Heat generation expenditure factor of heat generator 3 for space heating system	Not used
$e_{g,w,1}$	Heat generation expenditure factor of heat generator 1 for domestic hot water system	Direct electricity (Loga and Diefenbach, 2013)
$e_{g,w,2}$	Heat generation expenditure factor of heat generator 2 for domestic hot water system	Not used
$e_{g,w,3}$	Heat generation expenditure factor of heat generator 3 for domestic hot water system	Not used
$g_{gl,n}$	Total solar energy transmittance for radiation perpendicular to the glazing	Depending on U-value of window, value found in: (TABULA, 2013)
$I_{sol,hor}$	Average global irradiation on horizontal surface during the heating season	Found from two sources: (Olseth and Skartveit,

$I_{sol,east}$	Average global irradiation on surfaces with orientation east during heating season	1987) and (Norsk Standard, 2011)
$I_{sol,west}$	Average global irradiation on surfaces with orientation west during heating season	
$I_{sol,north}$	Average global irradiation on surfaces with orientation north during heating season	
$I_{sol,south}$	Average global irradiation on surfaces with orientation south during heating season	
ϑ_{int}	The internal temperature (set-point temperature for space heating)	(Mjønes et al., 2012)
ϑ_e	The temperature of the external environment (average value during heating season)	(Olseth and Skartveit, 1987) and (Norsk Standard, 2011)
$n_{air,use}$	Average air change rate during heating season, related to the utilisation of the building	(Mjønes et al., 2012)
$n_{air,infiltr}$	Air change by infiltration (see TABULA values)	(Loga and Diefenbach, 2013)
$\eta_{ve,rec}$	Efficiency of ventilation heat recovery	TEK 10 and NS3700
$q_{s,w,h}$	Recoverable heat loss of the storage of domestic hot water system per m2 reference floor area	German values for direct electric heating (TABULA, 2013)
$q_{d,w,h}$	Recoverable heat loss of the distribution system of the domestic hot water per m2 reference floor area	
$q_{s,h}$	Annual effective heat loss of space heating storage per m2 reference floor area	No storage of heat
$q_{d,h}$	Annual effective heat loss of space heating distribution system per m2 reference floor area	No storage of heat
$q_{nd,w}$	Annual energy need for domestic hot water per m2 reference floor area	(Norsk Standard, 2011)
$q_{s,w}$	Annual heat loss of the DHW storage per m2 reference floor area	German values for direct electric heating (TABULA, 2013)
$q_{d,w}$	Annual heat loss of the DHW distribution system per m2 reference floor area	
$R_{0,wall}$	Thermal resistance of the walls in original state	(Mjønes et al., 2012)
$R_{0>window}$	Thermal resistance of the windows in original state	
$R_{0,floor}$	Thermal resistance of the floor in original state	
$R_{0,door}$	Thermal resistance of the door in original state	

$R_{0,roof}$	Thermal resistance of the roof in original state	
$R_{measure,wall}$	Additional thermal resistance of a thermal refurbishment measure applied to element wall	Based on U-values from either (Mjønes et al., 2012), TEK 10 or NS 3700
$R_{measure>window$	Additional thermal resistance of a thermal refurbishment measure applied to element window	
$R_{measure,floor}$	Additional thermal resistance of a thermal refurbishment measure applied to element floor	
$R_{measure,door}$	Additional thermal resistance of a thermal refurbishment measure applied to element door	
$R_{measure,roof}$	Additional thermal resistance of a thermal refurbishment measure applied to element roof	
$R_{add,wall}$	Additional thermal resistance due to unheated space bordering at the construction element wall	As the Enova report calculated U-values for the original elements as effective U-values, taking cold adjacent rooms/attics etc. into account, these are always set to 0.
$R_{add>window$	Additional thermal resistance due to unheated space bordering at the construction element window	
$R_{add,floor}$	Additional thermal resistance due to unheated space bordering at the construction element floor	
$R_{add,door}$	Additional thermal resistance due to unheated space bordering at the construction element door	
$R_{add,roof}$	Additional thermal resistance due to unheated space bordering at the construction element roof	
ΔU_{tbr}	Surcharge on all U-values	Based on (Loga and Diefenbach, 2013) in combination with TEK 10 and NS 3700.

Results

Energy demand

The delivered energy demand, including energy demand for space heating, technical appliances, lighting and DHW was found as displayed in Table 43 and Table 43. The results show the delivered energy for space heating as calculated from the Energy Balance model, and standardized net energy demand following NS 3031. Therefore these results do not show the correct total delivered energy demand for the buildings, as losses for DHW, lighting and technical appliances have not been accounted for.

Table 43: Results regarding energy demand from the MSc Project

	> 1956		1956 - 1970		1971 - 1980	
	Original envelope	Historical rehabilitation	Original envelope	Historical rehabilitation	Original envelope	Historical rehabilitation
Delivered energy for space heating [kWh/(m ² ·year)]	282.1	150.1	196.5	124.5	166.5	122.6
Net energy needed for technical appliances [kWh/(m ² ·year)]	17.5	17.5	17.5	17.5	17.5	17.5
Net energy needed for lighting [kWh/(m ² ·year)]	11.4	11.4	11.4	11.4	11.4	11.4
Net energy needed for DHW	29.8	29.8	29.8	29.8	29.8	29.8
Total delivered energy demand [kWh/(m ² ·year)]	340.8	208.8	255.2	183.2	225.2	181.3

Table 44: Results regarding energy demand from the MSc Project

	> 1956		1956 - 1970		1971 - 1980	
	TEK 10 Enova rehab.	Passive House rehab.	TEK 10 Enova rehab.	Passive House rehab.	TEK 10 Enova rehab.	Passive House rehab.
Delivered energy for space heating [kWh/(m ² ·year)]	93.6	66.3	90.4	61.9	80.4	52.4
Net energy needed for technical appliances [kWh/(m ² ·year)]	17.5	17.5	17.5	17.5	17.5	17.5
Net energy needed for lighting [kWh/(m ² ·year)]	11.4	11.4	11.4	11.4	11.4	11.4
Net energy needed for DHW	29.8	29.8	29.8	29.8	29.8	29.8
Total delivered energy demand [kWh/(m ² ·year)]	152.3	125.0	149.1	120.6	139.1	111.1

As the results from the MSc Project work shows, the energy demand will decrease with increased energy rehabilitation. As the tables below reveal the rehabilitated buildings can achieve the TEK 10 energy requirement if balance ventilation with heat recovery is applied. The Passive House level was not achieved even with heat recovery of the ventilation air.

Table 45: TEK 10 energy requirements

TEK 10 Energy requirements		
Total net energy demand for building [kWh/(m ² ·year)]		
> 1956	1956 - 1970	1971 - 1980
131.0	130.5	130.5

Table 46: Passive House energy requirements

Passive house requirements		
Net energy demand for space heating [kWh/(m ² ·year)]		
> 1956	1956 - 1970	1971 - 1980
20.6	20.6	20.3

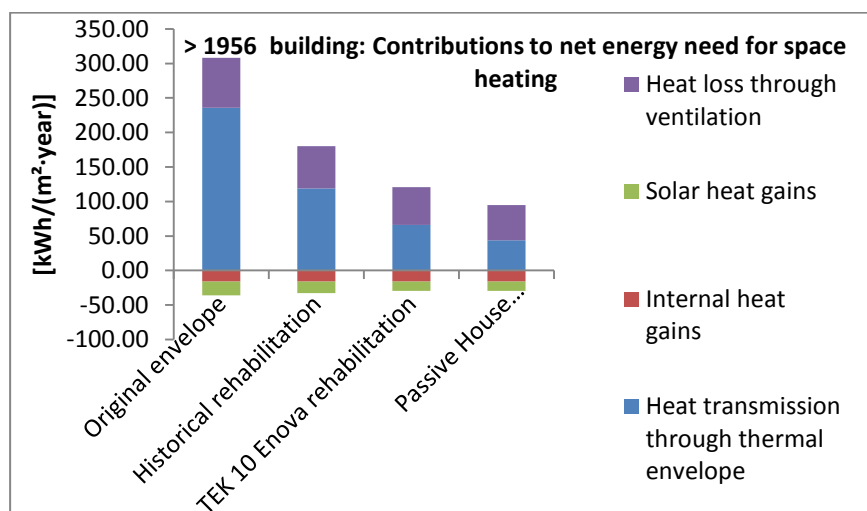
Table 47: Energy demand with TEK 10 rehabilitation

TEK 10 Enova rehabilitation		
Total net energy demand for building [kWh/(m ² ·year)]		
> 1956	1956 - 1970	1971 - 1980
113.8	113.7	109.7

Table 48: Energy demand with Passive House rehabilitation

Passive House rehabilitation		
Net energy demand for space heating [kWh/(m ² ·year)]		
> 1956	1956 - 1970	1971 - 1980
26.7	26.2	23.6

Net energy need for space heating, influencing factors

**Figure 34: Contributions to net energy need for space heating**

For all age cohorts the heat losses and gains were evaluated. The results were similar for all age cohorts and thus only the result for one age cohort has been displayed. As can be seen from Figure 34 the heat losses through the thermal envelope and the ventilation system are substantial. For the original and historically upgraded buildings the most contributing factor is without question the heat transmission through the thermal envelope. For the better insulated

buildings the heat loss through ventilation becomes increasingly important. Based on these results the conclusion from the MSc Project thesis was that for older buildings better insulation is the first measure to realize energy savings. When the buildings are insulated ventilation systems with heat recovery becomes very important.

Heat transmission through building envelope, influencing factors

As heat transmission through the building envelope was found to be an important contributor to the energy demand of the building it was investigated further. As Figure 35 shows the heat transmission through each building element was calculated.

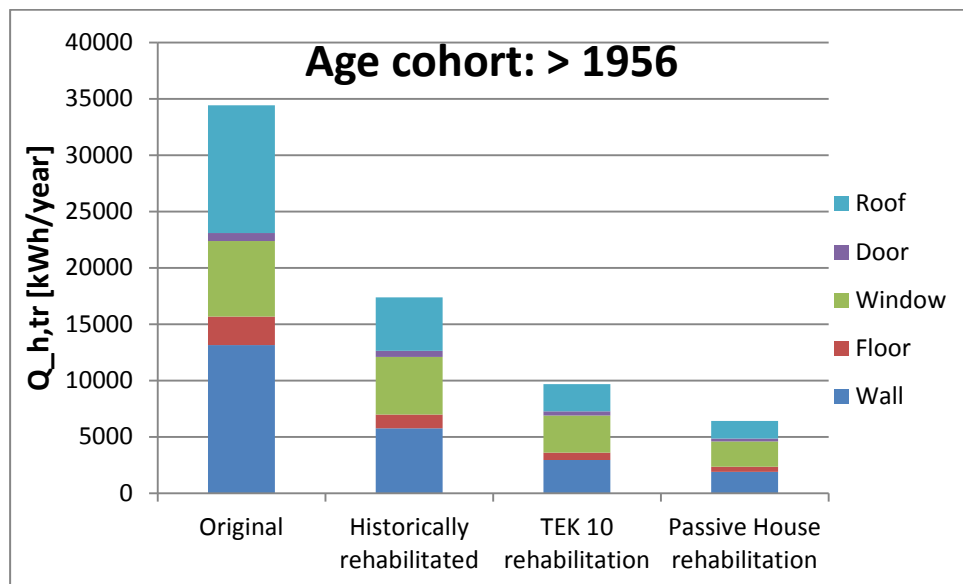


Figure 35: Heat transmission through the building envelope

The heat transmission through the walls and roof was found to be most important. The windows accounted for a large share of the heat transmission considering the relatively small area compared to the rest of the building envelope. The floor was found to account for a small share of the heat transmission.

Differences across climate zones

Norway is a very long and narrow country with varying climatic conditions. To account for this the energy demand was calculated for 7 climate zones, in addition to the Oslo climate, zone 9, and the mean climate values, zone 8.

Table 49 Net energy demand depending on climate zone

Climate zone	Original building from before 1956									
	Historically rehabilitation					TEK 10 Enova rehabilitation				
	Net energy need for space heating [kWh/(m ² -yr)]	Solar heat gains [kWh/(m ² -yr)]	Internal heat gains [kWh/(m ² -yr)]	Heat transfer by ventilation [kWh/(m ² -yr)]	Heat transfer by transmission [kWh/(m ² -yr)]	Net energy need for space heating [kWh/(m ² -yr)]	Solar heat gains [kWh/(m ² -yr)]	Internal heat gains [kWh/(m ² -yr)]	Heat transfer by ventilation [kWh/(m ² -yr)]	Heat transfer by transmission [kWh/(m ² -yr)]
1	146.2	23.8	16.5	63.3	123.2	89.4	19.1	16.7	56.6	68.6
2	122.8	18.5	15.6	53.2	103.6	74.7	14.8	15.8	47.6	57.7
3	181.5	28.1	18.4	77.4	150.7	111.9	22.6	18.6	69.2	84.0
4	135.4	22.4	17.4	59.4	115.7	82.1	17.9	17.5	53.1	64.5
5	184.3	24.5	18.4	77.1	150.1	114.3	19.7	18.6	68.9	83.6
6	170.6	25.7	19.0	73.0	142.2	104.7	20.6	19.2	65.3	79.2
7	216.8	30.7	21.3	91.3	177.6	134.3	24.7	21.6	81.6	99.0
8	164.0	24.8	18.1	70.2	136.6	100.7	19.9	18.3	62.7	76.1
9	147.2	17.0	16.0	61.1	118.9	91.2	13.6	16.1	54.6	66.3

As can be seen from

Table 49 the difference in energy demand across the country is significant. The Oslo climate is often used when calculating energy demand, as it's used for the standard values given in the Norwegian Standard NS 3031. The largest deviations from the Oslo climate were found in the northern parts of Norway as well as the mountain areas. As the largest cities in Norway is not located in these areas it was concluded that when calculating the energy demand of the Norwegian building stock the Oslo climate should be adequate as a reference point. However, it was argued that a weighted average of the 7 climate zones might give better results.

Appendix E Assumptions and results MSc

Thesis Energy balance

Assumptions

Summary of changing parameters and the sources:

In the following table all parameters that are changed during the calculations are summarized together with the sources values have been based on.

<u>Parameter</u>	<u>Description</u>	<u>Source</u>
$A_{C,ref}$	Reference area	(Mjønes et al., 2012)
$A_{window,hor}$	Area of all windows with horizontal orientation	
$A_{window,east}$	Area of all windows with orientation east	
$A_{window,west}$	Area of all windows with orientation west	
$A_{window,north}$	Area of all windows with orientation north	
$A_{window,south}$	Area of all windows with orientation south	
$A_{env,wall}$	Area of envelope area wall	
$A_{env>window}$	Area of envelope area window	
$A_{env,floor}$	Area of envelope area floor	
$A_{env,door}$	Area of envelope area door	
$A_{env,roof}$	Area of envelope area roof	
$\alpha_{nd,h,1}$	Fraction of heat generator 1 for space heating system	Depends on rehabilitation package
$\alpha_{nd,h,2}$	Fraction of heat generator 2 for space heating system	
$\alpha_{nd,h,3}$	Fraction of heat generator 3 for space heating system	
$\alpha_{nd,w,1}$	Fraction of heat generator 1 for domestic hot water system	

$\alpha_{nd,w,2}$	Fraction of heat generator 2 for domestic hot water system	
$\alpha_{nd,w,3}$	Fraction of heat generator 3 for domestic hot water system	
d_{hs}	Length of the heating season	(Olseth and Skartveit, 1987) and (Norsk Standard, 2011)
$e_{g,h,1}$	Heat generation expenditure factor of heat generator 1 for space heating system	Direct electricit
$e_{g,h,2}$	Heat generation expenditure factor of heat generator 2 for space heating system	Wood
$e_{g,h,3}$	Heat generation expenditure factor of heat generator 3 for space heating system	Heat Pump or Biomass boiler
$e_{g,w,1}$	Heat generation expenditure factor of heat generator 1 for domestic hot water system	Direct electricity
$e_{g,w,2}$	Heat generation expenditure factor of heat generator 2 for domestic hot water system	Heat Pump or Biomass boiler
$e_{g,w,3}$	Heat generation expenditure factor of heat generator 3 for domestic hot water system	Not used
$g_{gl,n}$	Total solar energy transmittance for radiation perpendicular to the glazing	Depending on U-value of window, value found in: (TABULA, 2013)
$I_{sol,hor}$	Average global irradiation on horizontal surface during the heating season	Found from two sources: (Olseth and Skartveit, 1987) and (Norsk Standard, 2011)
$I_{sol,east}$	Average global irradiation on surfaces with orientation east during heating season	
$I_{sol,west}$	Average global irradiation on surfaces with orientation west during heating season	
$I_{sol,north}$	Average global irradiation on surfaces with orientation north during heating season	

$I_{\text{sol,south}}$	Average global irradiation on surfaces with orientation south during heating season	
ϑ_{int}	The internal temperature (set-point temperature for space heating)	(Mjønes et al., 2012)
ϑ_e	The temperature of the external environment (average value during heating season)	(Olseth and Skartveit, 1987) and (Norsk Standard, 2011)
$n_{\text{air,use}}$	Average air change rate during heating season, related to the utilisation of the building	(Mjønes et al., 2012)
$n_{\text{air,infiltr}}$	Air change by infiltration (see TABULA values)	(Loga and Diefenbach, 2013)
$\eta_{\text{ve,rec}}$	Efficiency of ventilation heat recovery	TEK 10 and NS3700
$q_{\text{s,w,h}}$	Recoverable heat loss of the storage of domestic hot water system per m2 reference floor area	German values for direct electric heating (TABULA, 2013)
$q_{\text{d,w,h}}$	Recoverable heat loss of the distribution system of the domestic hot water per m2 reference floor area	
$q_{\text{s,h}}$	Annual effective heat loss of space heating storage per m2 reference floor area	No storage of heat
$q_{\text{d,h}}$	Annual effective heat loss of space heating distribution system per m2 reference floor area	No storage of heat
$q_{\text{nd,w}}$	Annual energy need for domestic hot water per m2 reference floor area	(Norsk Standard, 2011)
$q_{\text{s,w}}$	Annual heat loss of the DHW storage per m2 reference floor area	German values for direct electric heating, and Danish values for central heating (35% loss)(TABULA, 2013)
$q_{\text{d,w}}$	Annual heat loss of the DHW distribution system per m2 reference floor area	
$R_{0,\text{wall}}$	Thermal resistance of the walls in original state	(Mjønes et al., 2012)
$R_{0,\text{window}}$	Thermal resistance of the windows in original	

	state	
$R_{0,\text{floor}}$	Thermal resistance of the floor in original state	
$R_{0,\text{door}}$	Thermal resistance of the door in original state	
$R_{0,\text{roof}}$	Thermal resistance of the roof in original state	
$R_{\text{measure,wall}}$	Additional thermal resistance of a thermal refurbishment measure applied to element wall	Based on U-values from either (Mjønes et al., 2012), TEK 10 or NS 3700
$R_{\text{measure>window}$	Additional thermal resistance of a thermal refurbishment measure applied to element window	
$R_{\text{measure,floor}}$	Additional thermal resistance of a thermal refurbishment measure applied to element floor	
$R_{\text{measure,door}}$	Additional thermal resistance of a thermal refurbishment measure applied to element door	
$R_{\text{measure,roof}}$	Additional thermal resistance of a thermal refurbishment measure applied to element roof	
$R_{\text{add,wall}}$	Additional thermal resistance due to unheated space bordering at the construction element wall	As the Enova report calculated U-values for the original elements as effective U-values, taking cold adjacent rooms/attics etc. into account, these are always set to 0.
$R_{\text{add>window}$	Additional thermal resistance due to unheated space bordering at the construction element window	
$R_{\text{add,floor}}$	Additional thermal resistance due to unheated space bordering at the construction element floor	
$R_{\text{add,door}}$	Additional thermal resistance due to unheated space bordering at the construction element door	
$R_{\text{add,roof}}$	Additional thermal resistance due to unheated space bordering at the construction element roof	
ΔU_{tbr}	Surcharge on all U-values	Held constant except from

		sensitivity analysis (chapter 3.2)
--	--	---------------------------------------

Table 50: Varying α_{nd} for different heating solutions

α_{nd} varying with rehabilitation packages				
	Direct el	Heat Pump (A-to-A)	Heat Pump (A-to-W)	Biomass boiler
$\alpha_{nd,h,1}$ (direct el)	0.9	0	0	0.1
$\alpha_{nd,h,2}$ (Wood)	0.1	0.2	0.2	0
$\alpha_{nd,h,3}$ (HP or Bb)	0	0.8	0.8	0.9
$\alpha_{nd,w,1}$ (direct el)	1	1	0.2	0.1
$\alpha_{nd,w,2}$ (HP)	0	0	0.8	0
$\alpha_{nd,w,3}$ (Bb)	0	0	0	0.9

Results

Table 51: Total delivered energy demand for each case

Total energy demand [kWh/year]						
Cases	ED Space Heating	ED DHW	Direct el	Wood	Biopellets	Heat Pump
<i>Base Case</i>						
> 1956	20469	4979	22420	3028	0	0
1956 - 1970	18528	4979	20766	2741	0	0
1970 - 1980	20134	5183	22339	2978	0	0
<i>R 1.0.1</i>						
> 1956	17681	4979	20044	2616	0	0
1956 - 1970	16305	4979	18872	2412	0	0
1970 - 1980	16959	5183	19633	2509	0	0
<i>R 1.0.2</i>						
> 1956	15201	4979	17931	2249	0	0
1956 - 1970	13955	4979	16870	2064	0	0
1970 - 1980	14588	5183	17613	2158	0	0
<i>R 1.1.1</i>						

> 1956	9057	4979	4979	5231	0	3826
1956 - 1970	8352	4979	4979	4824	0	3528
1970 - 1980	8687	5183	5183	5017	0	3670
R 1.1.2						
> 1956	7787	4979	4979	4497	0	3290
1956 - 1970	7149	4979	4979	4129	0	3020
1970 - 1980	7473	5183	5183	4316	0	3157
R 2.0.1						
> 1956	15264	4979	17984	2258	0	0
1956 - 1970	15312	4979	18026	2265	0	0
1970 - 1980	15926	5183	18753	2356	0	0
R 2.0.2						
> 1956	12116	4979	15302	1792	0	0
1956 - 1970	12212	4979	15384	1807	0	0
1970 - 1980	12774	5183	16068	1890	0	0
R 2.1.1						
> 1956	7819	4979	4979	4516	0	3303
1956 - 1970	7844	4979	4979	4530	0	3314
1970 - 1980	8158	5183	5183	4712	0	3446
R 2.1.2						
> 1956	6207	4979	4979	3585	0	2622
1956 - 1970	6256	4979	4979	3613	0	2643
1970 - 1980	6544	5183	5183	3779	0	2764
R 3.0						
> 1956	12446	4979	15583	1841	0	0
1956 - 1970	12659	4979	15765	1873	0	0
1970 - 1980	13298	5183	16514	1967	0	0
R 3.1						
> 1956	9970	4979	13474	1475	0	0
1956 - 1970	10436	4979	13871	1544	0	0
1970 - 1980	11513	5183	14993	1703	0	0
R 3.2						
> 1956	5107	4979	4979	2950	0	2157
1956 - 1970	5346	4979	4979	3088	0	2258
1970 - 1980	5897	5183	5183	3406	0	2491
R 3.3						
> 1956	3605	2519	2941	0	0	3183
1956 - 1970	3779	2519	3028	0	0	3270
1970 - 1980	4179	2623	3275	0	0	3527

R 3.4						
> 1956	11039	6975	1471	0	16544	0
1956 - 1970	11573	6975	1514	0	17034	0
1970 - 1980	12799	7262	1638	0	18423	0
R 4.0						
> 1956	10623	4979	14030	1571	0	0
1956 - 1970	11572	4979	14839	1712	0	0
1970 - 1980	13215	5183	16443	1955	0	0
R 4.1						
> 1956	5504	4979	9669	814	0	0
1956 - 1970	5904	4979	10009	873	0	0
1970 - 1980	7124	5183	11253	1054	0	0
R 4.2						
> 1956	2820	4979	4979	1628	0	1191
1956 - 1970	3024	4979	4979	1747	0	1278
1970 - 1980	3649	5183	5183	2108	0	1542
R 4.3						
> 1956	1914	2519	2096	0	0	2337
1956 - 1970	2062	2519	2170	0	0	2411
1970 - 1980	2517	2623	2444	0	0	2696
R 4.4						
> 1956	5860	6975	1048	0	11788	0
1956 - 1970	6315	6975	1085	0	12205	0
1970 - 1980	7709	7262	1222	0	13748	0
R 5.1						
> 1956	1914	2519	2096	0	0	2337
1956 - 1970	2062	2519	2170	0	0	2411
1970 - 1980	2517	2623	2444	0	0	2696

Table 52: Heat transmission losses and Dimensioned Power demand

		R 1.1.1	R 1.1.2	R 2.1.1	R 2.1.2	R 3.2	R 3.3	R 3.4	R 4.2	R 4.3	R 4.4	R 5.1
H_ve [W/K]	> 1956	78.3	78.3	78.3	78.3	24.6	24.6	24.6	13.9	13.9	13.9	13.9
	1956 -											
	1970	74.5	74.5	74.5	74.5	25.3	25.3	25.3	14.4	14.4	14.4	14.4
	1970 -											
	1980	73.2	73.2	73.2	73.2	27.1	27.1	27.1	15.5	15.5	15.5	15.5
H_tr [W/K]	> 1956	158.4	131.1	131.8	97.7	127.1	127.1	127.1	90.6	90.6	90.6	90.6
	1956 -											
	1970	130.6	106.4	120.4	88.7	119.1	119.1	119.1	84.8	84.8	84.8	84.8
	1970 -											
	1980	140.3	115.9	129.7	97.4	129.7	129.7	129.7	97.4	97.4	97.4	97.4
P_dim [kW]	> 1956	9.0	8.0	8.0	6.7	5.8	7.8	7.8	4.0	6.0	6.0	6.0
	1956 -											
	1970	8.0	7.1	7.6	6.4	5.6	7.6	7.6	3.9	5.9	5.9	5.9
	1970 -											
	1980	8.3	7.4	7.9	6.7	6.1	8.1	8.1	4.4	6.4	6.4	6.4
P_dim_base [kW]	> 1956	5.4	4.8	4.8	4.0	3.5	4.7	4.7	2.4	3.6	3.6	3.6
	1956 -											
	1970	4.8	4.2	4.6	3.8	3.4	4.6	4.6	2.3	3.5	3.5	3.5
	1970 -											
	1980	5.0	4.4	4.7	4.0	3.7	4.9	4.9	2.6	3.8	3.8	3.8
P_dim_peak [kW]	> 1956	3.6	3.2	3.2	2.7	2.3	3.1	3.1	1.6	2.4	2.4	2.4
	1956 -											
	1970	3.2	2.8	3.0	2.5	2.3	3.1	3.1	1.5	2.3	2.3	2.3
	1970 -											
	1980	3.3	3.0	3.2	2.7	2.4	3.2	3.2	1.8	2.6	2.6	2.6

Appendix F The rehabilitation packages

Table 53: All rehabilitation packages

Rehabilitation package	Passive Measures	Active Measures
1.0.1	Tek 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors 	
1.0.2	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors 	
1.1.1	Tek 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors 	Installation of an Air-to-Air Heat Pump
1.1.2	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors 	Installation of an Air-to-Air Heat Pump
2.0.1	Tek 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof 	
2.0.2	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof 	
2.1.1	Tek 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof 	Installation of an Air-to-Air Heat Pump
2.1.2	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof 	Installation of an Air-to-Air Heat Pump
3.0	TEK 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	

3.1	TEK 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70%
3.2	TEK 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70% Air-to-Air Heat Pump for space heating. Wood stove for peak load Direct electricity for water heating
3.3	TEK 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70% Air-to-Water Heat Pump for space heating and DHW-heating Electric element in the DHW-tank provides peak load Requires installation of radiator for waterborne space heating
3.4	TEK 10 rehab of components: <ul style="list-style-type: none"> - Facade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70% Biomass-boiler for space heating and DHW-heating Electric element in DHW-tank provides peak load Requires installation of radiator for waterborne space heating
4.0	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	
4.1	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70%
4.2	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof 	Installation of Balanced Ventilation, Heat recovery of 70% Air-to-Air Heat Pump for space heating. Wood stove for peak load Direct electricity for water heating

	<ul style="list-style-type: none"> - Floor (for 2 of the age cohorts) 	
4.3	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70% Air-to-Water Heat Pump for space heating and DHW-heating Electric element in the DHW-tank provides peak load Requires installation of radiator for waterborne space heating
4.4	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70% Biomass-boiler for space heating and DHW-heating Electric element in DHW-tank provides peak load Requires installation of radiator for waterborne space heating
5.1	Passive House rehab of comp: <ul style="list-style-type: none"> - Façade - Windows - Doors - Roof - Floor (for 2 of the age cohorts) 	Installation of Balanced Ventilation, Heat recovery of 70% Air-to-Water Heat Pump for space heating and DHW-heating Electric element in the DHW-tank provides peak load Requires installation of radiator for waterborne space heating PV-panels for electricity production

Appendix G Assumptions for the Economic analysis

All cost components of the economic analysis

All passive cost components:

Table 54: Passive cost components

Element	Investment cost [NOK]	Lifetime	Source
Façade	Removing exterior cladding: 62.45 NOK/m ² New exterior cladding: 705.7 NOK/m ²	40 – 60 years	<u>Price:</u> Norsk Prisbok 13 <u>Lifetime:</u>
Changing windows	Installation: 1389.7 NOK/m ²		<u>Price:</u> Norsk Prisbok 13 <u>Lifetime:</u>
Changing doors	3381.3 NOK/m ²		<u>Price:</u> Norsk Prisbok 13 <u>Lifetime:</u>
Window u-value = 1.4 W/m ² K	3973 NOK/m ²	25 years	<u>Price:</u> Calculated based on the prices for the other windows. <u>Lifetime:</u>
Window u-value = 1.2 W/m ² K	4447 NOK/m ²	25 years	<u>Price:</u> Norsk Prisbok 13 <u>Lifetime:</u>
Window u-value = 0.7 W/m ² K	4979 NOK/m ²	25 years	<u>Price:</u> Norsk Prisbok 13 <u>Lifetime:</u>
New door	9969 NOK/m ²	25 years	<u>Price:</u> Norsk Prisbok 13 <u>Lifetime:</u>
<i>Insulation thickness</i> <i>[mm]</i>	<i>[kr/m² wall]</i> 19.8 27 37.5 47 55.8 60.1 74.3 93.2 115.9		Rockwool

All active cost components:

Table 55: Active cost components

Element	Investment cost [NOK]	Maintenance cost [NOK/year]	Lifetime [years]	Source
Heat Pump A-t-A	Power 3 kW: 22990 Power: 4 kW: 24990 Power 5 kW: 28990	5% of investment Power 3 kW: 575 Power 4 kW: 625 Power 5 kW: 725	10 years	<u>Investment costs:</u> Toshiba Daiseikai Polar (Toshiba, 2014) <u>Lifetime:</u> Varmepumpeinfo.no <u>Maintenance cost:</u> (Statsbygg, 2014)
Heat Pump A-t-W	Power 2-6 kW: 59000	5% of investment Power 2-6 kW: 1475	15 years	<u>Cost:</u> Investment: Toshiba kWsmart (Toshiba, 2014) Maintenance: (Statsbygg, 2014) <u>Lifetime:</u> Varmepumpeinfo.no
Pellets boiler	Frøling P1 7 kW: 78998 Silo for storage: 24500 Pumps etc: 13500 Installation: 50000	1500	20 years	<u>Investment, lifetime and maintenance:</u> SGP Varmeteknikk AS, Christian Brennum
DHW-tank for direct electricity	Oso Super S 200, 2 kW: 6500	As all cases includes a new DHW-tank, assumption is that maintenance cost is the same for all tanks, thus left out of the LCC	20-25 years	Oso Lifetime: Tom Røine (mail)
DHW-tank for use of HP/Pellets boiler	Oso Pionér EP: 18750 Including electric element for peak load			Oso Lifetime: Tom Røine (mail)
Waterborne space heating, radiators	957.9 [NOK/m ² floor area] <u>Total for building from:</u> > 1956: 139849.75 1956 – 1970: 139849.75 1970 – 1980: 145597		Very long lifetime, can exceed the house according to VVSforum.no 20-60 years (Norsk Prisbok)	Norsk Prisbok (Norconsult and AS Bygganalyse, 2013)
Ventilation system	<u>From Prisbok</u> 789.6 [NOK/m ² floor area]	200 NOK	15 – 60 years	<u>Investment cost:</u> Norsk Prisbok(Norconsult

Balanced ventilation	<u>Total for building from:</u> > 1956: 115285.25 1956 – 1970: 115285.25 1970 – 1980: 120023 <u>From Flexit:</u> System: 50000 Installation 15000			and AS Bygganalyse, 2013) Flexit: (Sætra, 2014) <u>Maintenance cost:</u> (Dokka and Wachenfeldt 2004)
Mechanical exhaust ventilation	<u>From Flexit:</u> The system: 10000 Installation: 10000			<u>Maintenance:</u> Assumed to be no maintenance costs
Direct electricity system	126 [NOK/m2 floor] <u>Total for building from:</u> > 1956: 18396 1956 – 1970: 18396 1970 – 1980: 19152	Assumed 0	20 – 30 years (chose 25)	<u>Price:</u> (Holthe AS, 2013) <u>Lifetime:</u> Norsk Prisbok (Norconsult and AS Bygganalyse, 2013)
New Wood Stove	7990 NOK	545 NOK/year	40 years	<u>Price and lifetime:</u> (Hofstad, 2014)
PV – panels	R 5.0: 251468 R 5.1: 146334	5% of investment	25 years	The prices are calculated based on (Multiconsult, 2013). Lifetime and maintenance based on the source as well.

Table 56: Energy prices

Energy prices [kr/kWh]		
Component	Cost	Source
Electricity	0.893	(SSB, 2014)
Wood	0.79	(Enok, 2014)
Biomass pellets	0.84	(Enova, 2014a)

Assumptions for the costs utilized in the LCC

- In all cases the investments are carried out in year 0, 2014, assuming that the buildings are so old they need upgrading now. This assumption disregards all possible upgrading's already done, assuming that this will be accounted for by basing the analysis on the numbers by Enova(Mjønes et al., 2012)
- The buildings energy balance is assumed to be constant over time, only changed by the rehabilitation packages implemented. Thus the annual energy cost will be constant as long as the energy prices are not changed.
- The price inflation is not taken into account in the analysis.
- The energy price for each energy carrier is assumed constant during the years 2014 – 2050. They will only be changed as part of a sensitivity analysis.
- Based on the components lifetime, some investments must be carried out more than once during the years 2014 – 2050. The subsequent investment will be based on the same costs as in year 2014, as inflation is disregarded.
- A straight line depreciation (Hastings, 2010) is chosen and for those components where the economic lifetime extends beyond year 2050, the resale value is calculated based on the last investment in the component in question, and given as a negative cost in year 2050.
- The insulation measures applied are assumed to be in accordance with the information given by Rockwool for the product “Flexi-A plate”. Whenever the calculated thickness required isn't in their price list, two or more thicknesses have been added, summing their price.(Rockwool, 2014)
- The additional insulation is assumed to be applied on the inside of the roof, as all buildings have an attic, and thus the cost of changing the roof will not be included in the analysis. Applying insulation on the walls is to some extent more complicated as the assumption is that the insulation is applied on the outside of the building. This will require the exterior cladding to be removed before the insulation is applied and reattached afterwards. As the buildings under consideration are quite old it is assumed that the exterior cladding would need to be changed at some point even without further upgrading of the thermal envelope. Therefore the cost of removing the old cladding and replacing it with new cladding is taken into account in the LCC, in all rehabilitation packages, as well as the Base Case.
- A main distinction of the space and DHW heating systems is made. In some of the packages the space heating will be through a waterborne system, while others will not have this. Whenever such a system is in place, the heating of hot water will be integrated in the same heating system. To take this into account the cost of DHW-tanks are included in the analysis as the cost of one fit to a waterborne system is much more costly than one only require an electric element.
- In order to choose a realistic price for the DHW heater the power requirement has to be calculated. This is done in accordance with ENØK Normtall, with 13 W/m^2 , giving a requirement of approximately 2 kW per dwelling. (Enova, 2004)

- Mechanical exhaust ventilation is assumed installed in year 0 for all packages where balanced ventilation isn't installed. The assumption is that some sort of exhaust ventilation will be used, as it is common to have extractor fans installed in kitchens and bathrooms.
- Maintenance cost for the roof and floor are assumed to be equal for all cases, and thus kept out of the analysis.
- The maintenance cost will be taken into account for the energy supply system and the ventilation system. It will not be taken into account for the thermal envelope, the waterborne space heating system nor for space heating based on direct electricity. It is assumed to be equal for all cases for the thermal envelope. Maintenance of the electric system will be required no matter which heat system is in place, as the building still requires electricity for other purposes. The maintenance cost related to the radiators is disregarded based on information from (Purmo, 2014).
- Insulation of the floor has been kept out of the analysis for the last age cohort, as this building is constructed on the ground. Insulation of the floor would therefore require removing the floor boards and applying more insulation. As a result the room height would decrease and the measure is therefore not likely to be carried out.
- The installation cost of the Heat Pumps and Biomass boiler have been based on the design power demand, calculated as given in chapter 3.4.3. Based on the calculations three different power demands was found, 3 kW, 4 kW and 5 KW. Norsk Prisbok gives the price for 3 kW and 4 kW (Norconsult and AS Bygganalyse, 2013). After comparing these prices to those given by Toshiba they seem overestimated (Toshiba, 2014). Toshiba's Heat Pump covering 5 kW costs approximately the same as the price of a 3 kW Heat Pump in Norsk Prisbok. As a lower installed power demand should induce a lower price the prices from Toshiba has been used in the calculations. Toshiba gives prices for three different power requirements for the Heat Pump Daiseikai Polar with nominell power demands corresponding to approximately 3 kW, 4 kW and 5 kW for the heat Pumps Daiseikai 25, Daiseikai 35 and Daiseikai 45, respectively (Toshiba, 2014).
- Both the numbers from Holthe Kalkulasjonsnøkkel (Holthe AS, 2013) and Norsk Prisbok (Norconsult and AS Bygganalyse, 2013) are given excluded Value Added Tax (VAT). To account for this taxation all prices from these sources has been calculated including 25% VAT, as given by (Skatteetaten, 2014).
- To investigate the economic implications of trying to reach a Nearly Zero Energy Building the last rehabilitation includes PV-panels for electricity generation. The value of this energy is depicted in the NPV as the energy times the electricity price, named the energy revenue. The assumption is thus that the building would be a net zero energy building during the year. When the electricity demand of the building is known the basic assumption is that the PV-panels would need to produce the same amount of electricity in order for this becoming a net Zero Energy Building. This would of course require the grid to be able to receive the electricity from the PV-

panels. Whether or not this is achievable with the current grid lines in Norway is seen as beyond the scope of the project.

Appendix H Results from the Economic analysis

Table 57: NPV calculations using balanced ventilation according to(Norconsult and AS Byggaanalyse, 2013)

	NPV [kr]			NPV [kr/m2]			Specific additional cost [kr/m2]		
	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980
BC	771661	692687	722056	5285	4744	4750	0	0	0
R 1.0.1	781413	703199	722647	5352	4816	4754	67	72	4
R 1.0.2	782897	700296	720614	5362	4797	4741	77	52	-9
R 1.1.1	708213	638705	652944	4851	4375	4296	-435	-370	-455
R 1.1.2	725387	641913	657157	4968	4397	4323	-317	-348	-427
R 2.0.1	767992	704335	723843	5260	4824	4762	-25	80	12
R 2.0.2	772291	703329	723787	5290	4817	4762	4	73	11
R 2.1.1	710088	646124	660674	4864	4426	4347	-422	-319	-404
R 2.1.2	725544	655975	671805	4969	4493	4420	-316	-251	-331
R 3.0	745840	681010	690086	5108	4664	4540	-177	-80	-210
R 3.1	858880	797170	818468	5883	5460	5385	597	716	634
R 3.2	821335	756673	774466	5626	5183	5095	340	438	345
R 3.3	955628	890353	906819	6545	6098	5966	1260	1354	1216
R 3.4	1214869	1153734	1181813	8321	7902	7775	3036	3158	3025
R 4.0	655741	584678	583718	4491	4005	3840	-794	-740	-910
R 4.1	770385	702273	713354	5277	4810	4693	-9	66	-57
R 4.2	761093	690454	692742	5213	4729	4558	-72	-15	-193
R 4.3	854877	783705	786148	5855	5368	5172	570	623	422
R 4.4	1073944	1006300	1021652	7356	6892	6721	2070	2148	1971
R 5.0	877201	860751	877201	6008	5896	5771	723	1151	1021
R 5.1	952595	887939	898676	6525	6082	5912	1239	1337	1162

Table 58: NPV calculations using balanced ventilation according to(Sætra, 2014)

	NPV [kr]			NPV [kr/m2]			Specific additional cost [kr/m2]		
	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980
BC	771661	692687	722056	5285	4744	4750	0	0	0
R 1.0.1	781413	703199	722647	5352	4816	4754	67	72	4
R 1.0.2	782897	700296	720614	5362	4797	4741	77	52	-9
R 1.1.1	708213	638705	652944	4851	4375	4296	-435	-370	-455
R 1.1.2	725387	641913	657157	4968	4397	4323	-317	-348	-427
R 2.0.1	767992	704335	723843	5260	4824	4762	-25	80	12
R 2.0.2	772291	703329	723787	5290	4817	4762	4	73	11
R 2.1.1	710088	646124	660674	4864	4426	4347	-422	-319	-404
R 2.1.2	725544	655975	671805	4969	4493	4420	-316	-251	-331
R 3.0	756951	692312	701958	5185	4742	4618	-101	-3	-132
R 3.1	786404	724694	739164	5386	4964	4863	101	219	113
R 3.2	748859	684197	695162	5129	4686	4573	-156	-58	-177
R 3.3	883152	817878	827515	6049	5602	5444	764	857	694
R 3.4	1142393	1081258	1102509	7825	7406	7253	2539	2661	2503
R 4.0	655741	584678	583718	4491	4005	3840	-794	-740	-910
R 4.1	697909	629798	634050	4780	4314	4171	-505	-431	-579
R 4.2	688617	617978	613437	4717	4233	4036	-569	-512	-715
R 4.3	782401	711229	706844	5359	4871	4650	74	127	-100
R 4.4	1001468	933824	942348	6859	6396	6200	1574	1652	1449
R 5.0	851184	788275	797897	5830	5399	5249	545	655	499
R 5.1	880120	815463	819372	6028	5585	5391	743	841	640

Table 59: NPV if no financial funding is given

	NPV [kr]			NPV [kr/m2]			Specific additional cost [kr/m2]		
	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980	> 1956	1956 - 1970	1971 - 1980
BC	771661	692687	722056	5285	4744	4750	0	0	0
R 1.0.1	781413	703199	722647	5352	4816	4754	67	72	4
R 1.0.2	782897	700296	720614	5362	4797	4741	77	52	-9
R 1.1.1	708213	638705	652944	4851	4375	4296	-435	-370	-455
R 1.1.2	725387	641913	657157	4968	4397	4323	-317	-348	-427
R 2.0.1	767992	704335	723843	5260	4824	4762	-25	80	12
R 2.0.2	772291	703329	723787	5290	4817	4762	4	73	11
R 2.1.1	710088	646124	660674	4864	4426	4347	-422	-319	-404
R 2.1.2	725544	655975	671805	4969	4493	4420	-316	-251	-331
R 3.0	756951	692312	701958	5185	4742	4618	-101	-3	-132
R 3.1	786404	724694	739164	5386	4964	4863	101	219	113
R 3.2	748859	684197	695162	5129	4686	4573	-156	-58	-177
R 3.3	903152	837878	847515	6186	5739	5576	901	994	825
R 3.4	116239 3	1101258	1122509	7962	7543	7385	2676	2798	2635
R 4.0	743341	672278	674918	5091	4605	4440	-194	-140	-310
R 4.1	785509	717398	725250	5380	4914	4771	95	169	21
R 4.2	776217	705578	704637	5317	4833	4636	31	88	-115
R 4.3	888445	817273	817245	6085	5598	5377	800	853	626
R 4.4	110751 2	1039868	1052750	7586	7122	6926	2300	2378	2176
R 5.0	938784	875875	889097	6430	5999	5849	1145	1255	1099
R 5.1	986163	921507	929773	6755	6312	6117	1469	1567	1367

Appendix I Results from the Scenario model

Energy Scenario Development using Renovation lifetime 60 (5)

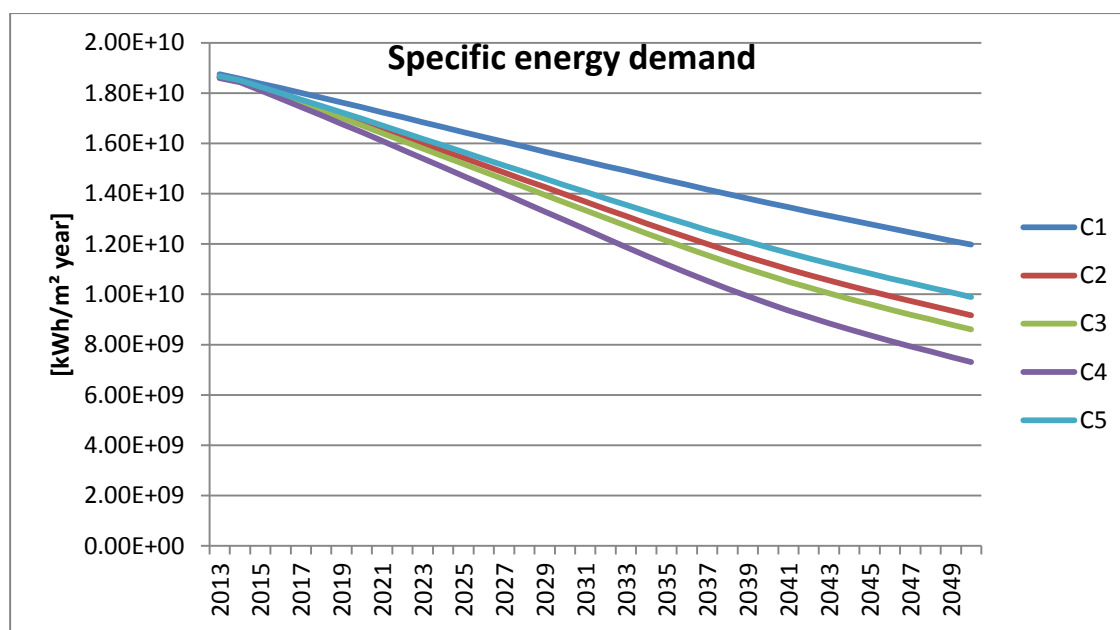


Figure 36: Energy scenario when using renovation lifetime 60 (5)

Future Energy and Emissions scenarios

Table 60: Energy demand and energy savings

Energy demand given as [TWh/m2]																								
year	Energy demand										Energy savings					Accumulated energy demand					Accumulated saving comp. To BC [TWh]			
	[TWh/year]										[TWh/year]					[TWh]								
	C0	C1	C2	C3	C4	C5	C2	C3	C4	C5	C0	C1	C2	C3	C4	C5	C2	C3	C4	C5				
2013	19	19	19	19	19	19	0	0	0	0	19	19	19	19	19	19	0	0	0	0				
2014	19	19	18	18	18	18	0	0	0	0	37	37	37	37	37	37	0	0	0	0				
2015	18	18	18	18	18	18	0	0	1	0	56	56	55	55	55	55	0	1	1	0				
2016	18	18	18	18	17	18	0	1	1	0	74	74	73	73	72	73	1	1	2	1				
2017	18	18	17	17	17	17	0	1	1	1	92	92	91	90	89	90	1	2	3	1				
2018	18	18	17	17	16	17	1	1	1	1	110	110	108	107	105	108	2	3	4	2				
2019	18	18	17	16	16	17	1	1	2	1	128	127	124	123	121	124	3	4	6	3				
2020	18	17	17	16	15	16	1	1	2	1	145	144	141	139	137	141	3	5	8	4				

2021	17	17	16	16	15	16	1	1	2	1	163	162	157	155	152	157	4	7	10	5
2022	17	17	16	15	15	16	1	2	2	1	180	178	173	170	166	173	5	8	12	6
2023	17	17	16	15	14	16	1	2	3	1	197	195	189	185	180	188	7	10	15	7
2024	17	17	15	15	14	15	1	2	3	1	214	212	204	200	194	204	8	12	18	8
2025	17	16	15	14	13	15	1	2	3	1	230	228	219	214	207	219	9	14	21	9
2026	16	16	15	14	13	15	1	2	3	1	247	244	233	228	220	233	11	16	24	11
2027	16	16	14	14	12	14	2	2	3	2	263	260	248	242	233	248	12	19	27	13
2028	16	16	14	13	12	14	2	2	4	2	279	276	262	255	245	262	14	21	31	14
2029	16	16	14	13	12	14	2	3	4	2	295	291	276	268	256	275	16	24	35	16
2030	16	15	13	13	11	13	2	3	4	2	311	307	289	280	268	289	17	26	39	18
2031	16	15	13	12	11	13	2	3	4	2	326	322	302	292	278	302	19	29	43	20
2032	15	15	13	12	10	13	2	3	4	2	342	337	315	304	289	315	21	32	48	22
2033	15	15	13	12	10	13	2	3	5	2	357	351	328	316	299	327	23	35	52	24
2034	15	15	12	11	10	12	2	3	5	2	372	366	340	327	309	340	26	39	57	26
2035	15	14	12	11	9	12	2	3	5	2	387	380	352	338	318	352	28	42	62	29
2036	15	14	12	11	9	12	2	4	5	2	402	394	364	349	327	363	30	46	68	31
2037	15	14	12	10	9	11	2	4	5	2	416	408	376	359	335	375	33	49	73	34
2038	14	14	11	10	8	11	2	4	6	3	430	422	387	369	344	386	35	53	79	36
2039	14	14	11	10	8	11	3	4	6	3	445	436	398	379	351	397	38	57	84	39
2040	14	13	11	9	7	11	3	4	6	3	459	449	409	388	359	408	40	61	90	42
2041	14	13	10	9	7	10	3	4	6	3	473	462	419	397	366	418	43	65	96	44
2042	14	13	10	9	7	10	3	4	6	3	486	475	430	406	373	428	46	69	103	47
2043	14	13	10	8	6	10	3	4	6	3	500	488	439	414	379	438	49	74	109	50
2044	13	13	10	8	6	10	3	5	7	3	513	501	449	423	385	448	52	78	116	53
2045	13	12	9	8	6	9	3	5	7	3	526	513	459	430	391	457	55	83	123	56
2046	13	12	9	8	5	9	3	5	7	3	539	526	468	438	396	466	58	88	130	60
2047	13	12	9	7	5	9	3	5	7	3	552	538	477	445	401	475	61	93	137	63
2048	13	12	9	7	5	9	3	5	7	3	565	550	485	452	405	483	64	98	144	66
2049	13	12	8	7	4	8	3	5	8	3	578	562	494	459	410	492	68	103	152	70
2050	12	12	8	6	4	8	3	5	8	4	590	573	502	465	413	500	71	108	160	74

Table 61: Total Emissions for the entire stock

	Total Emissions for entire stock [Mtons CO ₂ -eq/year]														
	Norwegian el. Mix					Nordic el. Mix					EU 27 el. Mix				
	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
2013	1.40	1.40	1.40	1.40	1.40	3.88	3.88	3.88	3.88	3.88	9.54	9.54	9.54	9.54	9.54
2014	1.39	1.39	1.38	1.37	1.41	3.84	3.82	3.80	3.80	3.82	9.44	9.36	9.34	9.34	9.34
2015	1.37	1.37	1.35	1.35	1.41	3.80	3.76	3.72	3.72	3.76	9.34	9.19	9.14	9.13	9.14
2016	1.36	1.36	1.32	1.32	1.41	3.76	3.69	3.65	3.64	3.70	9.24	9.01	8.94	8.93	8.94
2017	1.34	1.34	1.30	1.29	1.41	3.72	3.63	3.57	3.56	3.64	9.14	8.84	8.74	8.73	8.74
2018	1.33	1.32	1.27	1.26	1.41	3.68	3.56	3.49	3.48	3.59	9.04	8.67	8.55	8.54	8.55

2019	1.31	1.31	1.24	1.23	1.41	3.64	3.50	3.41	3.40	3.53	8.93	8.49	8.35	8.34	8.35
2020	1.30	1.29	1.22	1.20	1.41	3.59	3.43	3.33	3.32	3.47	8.83	8.32	8.16	8.14	8.16
2021	1.28	1.27	1.19	1.17	1.41	3.55	3.37	3.26	3.24	3.41	8.72	8.15	7.97	7.95	7.96
2022	1.27	1.26	1.16	1.14	1.40	3.51	3.31	3.18	3.16	3.35	8.62	7.98	7.78	7.76	7.77
2023	1.25	1.24	1.14	1.12	1.40	3.47	3.25	3.11	3.08	3.29	8.51	7.82	7.59	7.57	7.59
2024	1.24	1.22	1.11	1.09	1.40	3.42	3.18	3.03	3.01	3.23	8.41	7.65	7.41	7.38	7.40
2025	1.22	1.21	1.09	1.06	1.40	3.38	3.12	2.96	2.93	3.17	8.30	7.49	7.23	7.20	7.22
2026	1.21	1.19	1.06	1.03	1.39	3.34	3.06	2.89	2.86	3.11	8.20	7.33	7.05	7.02	7.04
2027	1.19	1.18	1.04	1.01	1.39	3.30	3.00	2.82	2.79	3.06	8.10	7.17	6.87	6.84	6.86
2028	1.18	1.16	1.02	0.98	1.39	3.26	2.95	2.75	2.71	3.00	7.99	7.02	6.70	6.66	6.69
2029	1.16	1.14	0.99	0.96	1.38	3.21	2.89	2.68	2.64	2.95	7.89	6.86	6.52	6.49	6.51
2030	1.15	1.13	0.97	0.93	1.38	3.17	2.83	2.61	2.57	2.89	7.79	6.71	6.35	6.32	6.34
2031	1.13	1.11	0.95	0.91	1.37	3.13	2.77	2.54	2.50	2.84	7.69	6.56	6.18	6.15	6.17
2032	1.12	1.10	0.92	0.88	1.37	3.09	2.72	2.48	2.44	2.78	7.59	6.41	6.02	5.98	6.01
2033	1.10	1.08	0.90	0.86	1.36	3.05	2.66	2.41	2.37	2.73	7.49	6.26	5.85	5.81	5.84
2034	1.09	1.07	0.88	0.83	1.36	3.01	2.60	2.34	2.30	2.68	7.39	6.11	5.69	5.64	5.67
2035	1.07	1.05	0.85	0.81	1.36	2.97	2.55	2.28	2.23	2.62	7.30	5.96	5.52	5.48	5.51
2036	1.06	1.04	0.83	0.78	1.35	2.93	2.49	2.21	2.17	2.57	7.20	5.82	5.36	5.31	5.35
2037	1.05	1.02	0.81	0.76	1.35	2.89	2.44	2.15	2.10	2.52	7.10	5.67	5.20	5.15	5.18
2038	1.03	1.01	0.79	0.74	1.34	2.85	2.38	2.08	2.03	2.47	7.01	5.53	5.04	4.99	5.02
2039	1.02	0.99	0.77	0.71	1.34	2.81	2.33	2.02	1.97	2.41	6.91	5.38	4.88	4.83	4.86
2040	1.00	0.98	0.74	0.69	1.34	2.78	2.28	1.96	1.90	2.36	6.82	5.24	4.72	4.67	4.70
2041	0.99	0.96	0.72	0.67	1.33	2.74	2.22	1.89	1.84	2.31	6.72	5.10	4.56	4.50	4.54
2042	0.98	0.95	0.70	0.64	1.33	2.70	2.17	1.83	1.77	2.26	6.63	4.95	4.40	4.35	4.38
2043	0.96	0.93	0.68	0.62	1.33	2.66	2.12	1.77	1.71	2.21	6.54	4.81	4.24	4.19	4.23
2044	0.95	0.92	0.66	0.60	1.32	2.62	2.06	1.70	1.64	2.16	6.45	4.67	4.09	4.03	4.07
2045	0.94	0.91	0.63	0.57	1.32	2.59	2.01	1.64	1.58	2.11	6.35	4.53	3.93	3.87	3.91
2046	0.92	0.89	0.61	0.55	1.32	2.55	1.96	1.58	1.51	2.06	6.26	4.39	3.78	3.71	3.76
2047	0.91	0.88	0.59	0.53	1.32	2.51	1.91	1.52	1.45	2.01	6.17	4.25	3.62	3.56	3.60
2048	0.90	0.86	0.57	0.50	1.31	2.48	1.86	1.46	1.39	1.97	6.09	4.12	3.47	3.40	3.45
2049	0.88	0.85	0.55	0.48	1.31	2.44	1.81	1.39	1.33	1.92	6.00	3.98	3.32	3.25	3.30
2050	0.87	0.84	0.53	0.46	1.31	2.41	1.75	1.33	1.26	1.87	5.91	3.85	3.17	3.10	3.15

Table 62: Accumulated emission savings compared to C1

Accumulated emission savings compared to C1 (BC) [Mtons CO2-eq]											
Norwegian el. Mix				Nordic el. Mix				EU 27 el. Mix			
C2	C3	C4	C5	C2	C3	C4	C5	C2	C3	C4	C5
0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.001	0.012	0.015	-	0.02	0.04	0.04	0.02	0.08	0.10	0.10	0.10

			0.017								
			-								
0.004	0.037	0.044	0.050	0.07	0.12	0.12	0.06	0.23	0.30	0.31	0.30
0.01	0.07	0.09	-0.10	0.14	0.23	0.25	0.12	0.45	0.60	0.62	0.60
0.01	0.12	0.15	-0.16	0.24	0.39	0.41	0.19	0.75	0.99	1.02	1.00
0.02	0.18	0.22	-0.24	0.35	0.58	0.62	0.28	1.12	1.48	1.52	1.49
0.03	0.25	0.31	-0.34	0.49	0.80	0.86	0.40	1.56	2.06	2.11	2.07
0.03	0.34	0.41	-0.45	0.65	1.06	1.13	0.52	2.06	2.72	2.80	2.74
0.04	0.43	0.52	-0.57	0.83	1.36	1.45	0.67	2.63	3.48	3.57	3.50
0.05	0.53	0.64	-0.71	1.03	1.68	1.80	0.83	3.26	4.31	4.43	4.34
0.07	0.64	0.78	-0.86	1.25	2.04	2.18	1.01	3.95	5.23	5.37	5.27
0.08	0.77	0.93	-1.02	1.49	2.43	2.59	1.20	4.71	6.23	6.39	6.27
0.09	0.90	1.09	-1.19	1.75	2.85	3.04	1.41	5.52	7.31	7.50	7.36
0.11	1.04	1.26	-1.38	2.02	3.31	3.52	1.64	6.39	8.46	8.68	8.52
0.12	1.19	1.44	-1.58	2.31	3.78	4.03	1.88	7.32	9.69	9.94	9.75
0.14	1.36	1.64	-1.79	2.62	4.29	4.57	2.13	8.29	10.99	11.27	11.06
0.15	1.52	1.84	-2.00	2.95	4.83	5.15	2.40	9.33	12.36	12.67	12.44
0.17	1.70	2.06	-2.24	3.29	5.39	5.74	2.68	10.41	13.79	14.15	13.89
0.19	1.89	2.28	-2.48	3.65	5.98	6.37	2.98	11.55	15.30	15.70	15.41
0.21	2.08	2.52	-2.73	4.03	6.59	7.03	3.28	12.73	16.88	17.31	16.99
0.23	2.29	2.76	-2.99	4.42	7.24	7.71	3.61	13.97	18.52	18.99	18.65
0.25	2.50	3.02	-3.26	4.83	7.90	8.42	3.94	15.26	20.22	20.75	20.37
0.27	2.72	3.29	-3.54	5.25	8.60	9.16	4.29	16.59	22.00	22.56	22.15
0.29	2.95	3.56	-3.84	5.68	9.32	9.93	4.65	17.97	23.83	24.45	24.00
0.32	3.18	3.85	-4.14	6.14	10.06	10.72	5.03	19.41	25.74	26.40	25.92
0.34	3.43	4.14	-4.45	6.61	10.83	11.54	5.41	20.89	27.71	28.42	27.91
0.37	3.68	4.44	-4.78	7.09	11.62	12.39	5.81	22.42	29.74	30.50	29.95
0.39	3.94	4.76	-5.11	7.59	12.44	13.26	6.23	24.00	31.84	32.66	32.07
0.42	4.21	5.08	-5.45	8.10	13.29	14.16	6.65	25.62	34.00	34.87	34.25
0.44	4.48	5.42	-5.81	8.63	14.16	15.09	7.09	27.30	36.23	37.16	36.49
0.47	4.77	5.76	-6.17	9.18	15.06	16.05	7.54	29.02	38.52	39.51	38.81
0.50	5.06	6.11	-6.55	9.74	15.98	17.03	8.00	30.80	40.87	41.93	41.18
0.53	5.36	6.47	-6.94	10.31	16.93	18.04	8.48	32.62	43.30	44.41	43.62
0.56	5.67	6.85	-7.33	10.90	17.90	19.08	8.97	34.49	45.78	46.96	46.13
0.59	5.99	7.23	-7.74	11.51	18.90	20.14	9.47	36.41	48.33	49.58	48.70
0.62	6.31	7.62	-8.16	12.13	19.92	21.23	9.98	38.38	50.95	52.26	51.34
0.65	6.64	8.02	-8.59	12.77	20.97	22.35	10.50	40.39	53.63	55.01	54.04
0.68	6.98	8.43	-9.03	13.42	22.04	23.49	11.04	42.46	56.37	57.82	56.80