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The effects on direct and indirect energy demand, carbon emissions and investment costs of adding supplementary wall insulation for Norwegian single-family houses built between 1971 and 1980

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Preface

This 30 ECTS (credit points) master's thesis has been written at the Department of Energy and Process Engineering (EPT) at the Norwegian University of Science and Technology. The work is linked to the EPISCOPE project, which is a follow-up project of the TABULA project.

The objective of this thesis has been to get a broader insight into the national potential of reducing the energy need and GHG emissions of Norwegian single-family houses built between 1971 and 1980 when refurbishing the façade and adding extra insulation. In collaboration with the supervisors, it was decided to change the time cohort of construction of the single-family houses from 1956 – 1970 to 1971 – 1980. This was because fewer buildings from the oldest time cohort were likely to refurbish than buildings from the newer time cohort from the year 2000 to 2050.

I have done a sensitivity analysis in the energy audit program, SIMIEN, of different parameters influencing the energy need for heating. Due to limited time, I have not managed to do a similar analysis in TABULA.

I would sincerely like to thank my supervisor Helge Brattebø and co-supervisor Nina H. Sandberg. The thesis work had not been possible without their guidance and constructive feedback, and I have learned a lot throughout this semester. I would also like to give acknowledgements to fellow students and family for valuable help and advices in the writing process.

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Abstract

In this report, I analyze the energy savings and carbon reduction potential of Norwegian single-family houses constructed between 1971 and 1980 (SFH03) when adding supplementary insulation to the outer walls. The report is split into two parts, where the first part consists of a material analysis and an energy audit for different façade refurbishments of a SFH03 building. The second part covers a scenario analysis of the different insulation solutions when modeling the SFH03 building stock segment in a dynamic building stock model from the year 2000 to 2050. Each insulation solution represents a unique renovation state in the SFH03 housing stock, with an associated annual heating demand calculated from the energy audit. In addition, renovation cycles, hence the time period between façade refurbishments, of 30, 40 and 50 years have been applied.

Vacuum insulation and mineral wool insulation are the two insulation types analyzed in the material analysis. However, mineral wool insulation is found to be a better material for façade refurbishment due to lower investment costs, lower indirect emissions and energy usage during manufacturing and a higher lifetime. Manufacturing vacuum insulation results in nine times more energy consumption and seven times more carbon emissions compared to manufacturing mineral wool corresponding to the same insulation solution.

The three different façade refurbishments assessed in the energy audit are, starting from the least ambitious refurbishment, historically refurbished state, approaching TEK 10 requirements and approaching passive house requirements. The annual energy need for heating for a chosen SFH03 building in original state amounts to 152 kWh/m^2. A façade refurbishment will result in significant energy savings, corresponding to the heating demand for the different renovation refurbishments of respectively 14, 24 and 30 kWh/m^2 for mineral wool insulation. Applying vacuum insulation will result in slightly lower energy savings, with a difference of respectively 1 kWh/m^2 for TEK 10 standard and 2 kWh/m^2 for passive house standard.

The objective of the report is to investigate the reduction potential of energy consumption and carbon emissions for the SFH03 dwelling stock segment towards 2050 when introducing more advanced insulation solutions for façade refurbishments. For the baseline scenario, the energy reduction potential in 2050 is almost 1/3 relative to 2010 for all renovation cycles. The baseline scenario corresponds to a scenario with an unchanged refurbishment policy, where historical façade refurbishment is conducted throughout the whole simulation period. All other scenarios, where more advanced insulation solutions are applied, will result in an even lower future heating demand. The carbon emission reduction potential is equal to the energy potential and achieves the same reduction in percentage as the energy consumption, hence 1/3 for the baseline scenario and lower for the remaining renovation solutions. The reduction potential is highly due to a larger share of demolished SFH03 dwellings in 2050.

Single-family houses accounts for almost 70 % of the Norwegian residential stock in 2012. The SFH03 stock segment accounts for about 13 % of these. By introducing a more ambitious renovation strategy of façade refurbishment for ageing single-family houses, this will contribute to reaching climate policy targets and achieving a significant reduction in energy usage and carbon emissions.

Sammendrag

I denne masteroppgaven analyserer jeg energibesparelser og utslippspotensialet for norske eneboliger bygget mellom 1971 og 1980 (SFH03) ved etterisolering av ytterveggene. Rapporten er todelt, hvor den første delen tar for seg en materialanalyse og energievaluering av SFH03-bygningen for forskjellige fasaderenoveringer. Den andre delen omfatter en scenarioanalyse for de forskjellige isolasjonsløsningene ved modellering av SFH03-boligsegmentet i en dynamisk boligmassemodell fra år 2000 til 2050. Hver isolasjonsløsning representerer en unik renoveringstilstand i SFH03-boligsegmentet, med et tilhørende energibehov for oppvarming beregnet fra energievalueringen. Det er i tillegg benyttet renoverinssykluser, det vil si tidsperioden mellom fasaderehabiliteringer, på 30, 40 og 50 år.

Vakuumisolasjon og mineralull er benyttet som hovedtyper i materialanalysen. Mineralull har imidlertid vist seg å være et bedre material til fasaderehabilitering, da det gir mindre investeringskostnader, har lavere indirekte utslipp og energibruk relatert til produksjon og har en høyere levetid. Til sammenligning, gir vakuumisolasjon i snitt ni ganger høyere energibruk og sju ganger høyere utslipp relatert til produksjon for samme isolasjonsløsning ved bruk av mineralull.

De tre forskjellige fasaderehabiliteringene i energievalueringen er, rangert fra den minst ambisiøse, historisk rehabilieringsnivå, tilnærmet TEK10-krav og tilnærmet passivhus-krav. Det årlige oppvarmingsbehovet til en SFH03-bygning i original tilstand tilsvarer 152 kWh/m^2. Rehabilitering av fasaden vil gi betydelige energibesparelser på henholdsvis 14, 24 og 30 kWh/m^2 for mineralull, avhengig av benyttet fasaderehabilitering. Ved bruk av vakuumisolasjon vil bruk av dette isolasjonsmaterialet resultere i hakket lavere energibesparelser, med en differanse på 1 kWh/m^2 for TEK10 og 2 kWh/m^2 passivhus-løsning.

Formålet med rapporten er å utforske reduksjonspotensialet i energibruk og CO_2-utslipp for SFH03-boligsegmentet frem mot 2050 når man introduserer mer avanserte løsninger for fasaderehabilitering. Baseline-scenarioet gir en energibesparelse på 1/3 relativt til 2010 ved vedlikeholdt renoveringsstrategi, det vil si at historisk rehabilitering er vedlikeholdt gjennom hele simuleringsperioden. Alle andre isolasjonsløsninger gir et desto lavere oppvarmingsbehov og energibruk. Potensialet i CO_2-besparelsene er lik energibesparelsene, det vil si 1/3 for baseline-scenarioet og lavere for de resterende ioslasjonsløsningene. Potensialet i energireduksjon og CO_2-besparelser skyldes i stor grad at en stor del av SFH03-segmentet er revet.

Ca. 70 % av den norske boligmassen i består av eneboliger i 2012. SFH03-boligsegmentet utgjør ca. 13 % av disse. Ved å innføre en mer ambisiøs renoveringsstrategi der fasaderehabilitering inngår for eldre eneboliger, vil energi- og utslippsbesparelsene bidra til å nå klimamål og å oppnå en betraktelig reduksjon i energibruk og CO_2-utslipp.

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Key terms and abbreviations

AB – Apartment Block. Apartment block includes residence for communities and other buildings.

BRA – (“Bruksareal”).The total utility floor space in a building.

Climate council – translated to “klimaforliket”.

CO_2 equivalents - The total CO_2 emissions related to operation of the dwelling per year.

Delivered energy - The energy delivered to the dwelling when losses are accounted for.

DHW – Domestic hot water.

Energy costs - The costs of energy delivered to a dwelling when emissions are accounted for.

Energy need – The calculated energy demand before applying any technical heating system.

EU – European Union.

GHG – Greenhouse gas.

IPCC - The intergovernmental Panel on Climate Change (known as “FNs klimapanel”).

Key Performance Indicators - Chosen parameters in the material analysis of insulation materials.

MFA – Material flow Analysis.

Primary energy - Energy in its pure form, which has not yet been transformed or converted.

Renovation cycle – Amount of years between façade refurbishments of a building.

SFH - Single-family house.

SFH03 – Single family house built in time cohort 3 (constructed between 1971 – 1980).

TH – Terraced House. House with two dwellings, row house or houses with three dwellings or more.

The EEA agreement – Agreement on the European Economic Area (known as “EØS-avtalen”).

The National Office of Building Technology and Administration – Translated to “Statens bygningstekniske etat”.

U-value – Is the thermal transmittance and measures the heat loss in a building from the building envelope. A high U-value corresponds to a high heat loss, and similarly, a low U-value corresponds to a low heat loss through the respective material.

1. Introduction

1.1 Objective and motivation

Single-family houses in Norway, built before 1990, represented more than 40 % of the total Norwegian dwelling stock in 2012 according to Statistics Norway (Prognosesenteret & Entelligens, 2011). These houses are in a technically worse condition and have less energy efficient building envelopes than newer houses of today's dwelling stock and may therefore represent huge energy savings if energy refurbishment measures are implemented on a massive scale (SINTEF Fag, 2014b).

Applying extra insulation to the outer walls of a building is known as an effective refurbishment measure for increased energy efficiency for dwellings constructed before 1980. This is due to significantly less strict U-value requirements in previous technical regulations for buildings (Risholt, 2013). The U-value for the outer walls of a building is a measure on the thermal transmittance through the building envelope and represents the heat loss.

The objective of this master's thesis is to investigate the future energy and carbon emission reduction potential when conducting different insulation solutions to the outer walls of an important segment of the Norwegian dwelling stock. The segment chosen in the analyses in this thesis is single-family houses constructed between 1971 and 1980. In the following, the example building will be referred to as an SFH03 building, where the number 03 corresponds to time cohort 3 of construction.

1.2 Research questions

In this master's thesis, I will carry out a two-part analysis of Norwegian single-family houses constructed between 1971 and 1980. The first part includes an energy audit of an example building representing an average synthetic single-family house built in the 1970s and a material analysis of mineral wool and vacuum insulation for different insulation thicknesses when refurbishing the outer walls. The second part consists of a scenario analysis of future refurbishment effects concerning the heating demand and carbon emission for different insulation solutions of the SFH03 dwelling stock segment examined.

In order to analyze and discuss the first part of the thesis work, the following research question must be answered:

Research question 1:
How do different insulation solutions for the outer walls affect the energy balance, material flows, investment costs and carbon emissions of single-family houses built between 1971 and 1980?

Energy and carbon emission calculations will be conducted in two energy audit models: SIMIEN and TABULA. The material analysis consists of key performance indicators (KPIs), including material consumption, waste at the construction-site, investment costs and upstream carbon emission and energy flows.

The energy results from the energy audit will be used as input in a dwelling stock model to obtain results on dwelling stock level. Obtaining these results will make it possible to gain the necessary knowledge to answer the final research question:

Research question 2:
How do different insulation solutions for the outer walls of single-family houses built between 1971 and 1980 influence the energy need for heating and carbon emissions towards 2050?

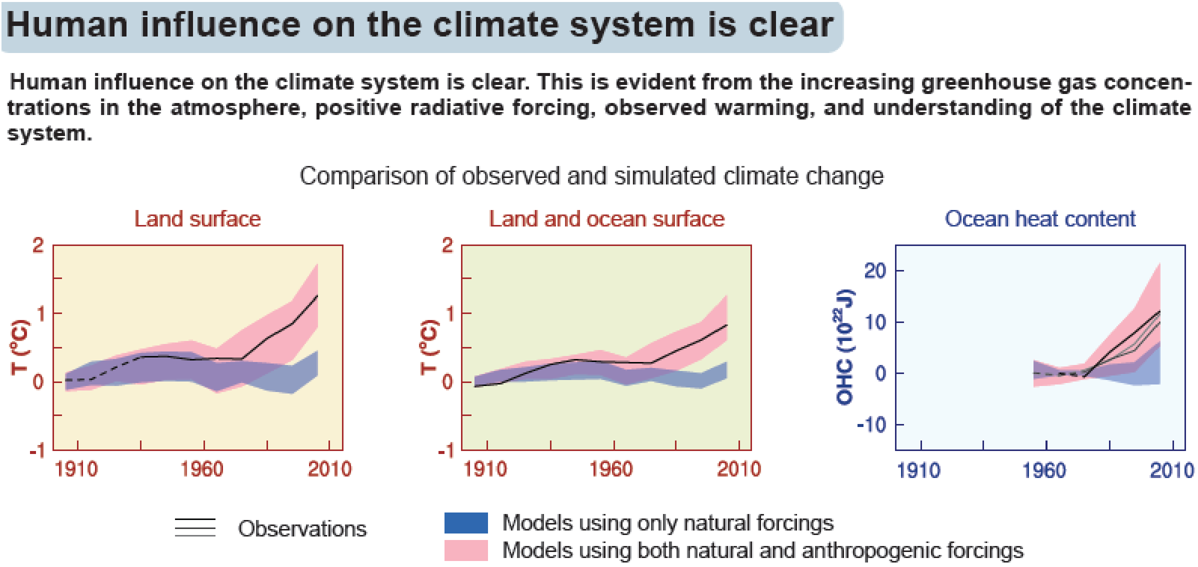
In order to investigate the reduction potential in energy usage and carbon emissions towards 2050, I will perform a scenario analysis in the dynamic building stock model. Each scenario will represent a unique insulation solution for façade refurbishment of the SFH03 building, corresponding to a respective annual heating demand. The scenarios include different time spans between refurbishment, hence different renovation cycles, of respectively 30, 40 and 50 years.

2. Context, theory and literature review

2.1 Political context

2.1.1 The European regulations

“Human influence on the climate system is clear”, states the Intergovernmental Panel on Climate Change, IPCC (2013), in their fifth assessment report on Climate Change. We humans are responsible for having emitted a significant share of the total GHG emissions over the last centuries. It is, however, interesting to see that despite a growing world economy, the global energy related emissions in 2014 remain unchanged compared to 2013, with a total amount of 32.3 billion tonnes CO_2. The executive director of the International Energy Agency, Maria van der Hoeven, points out that even though the latest emissions data is encouraging, this is not an excuse to not seek further implementation of energy mitigation strategies (IEA, 2015). According to IPCC, today’s most cost-efficient and simple climate measures are found in the building sector (IPCC, 2014; KrD, 2010).



Human influence on the climate system is clear

Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system.

Figure 1: Snapshot of the poster of the climate change report (IPCC, 2013)

Energy use in buildings represents about 40 % of the total energy use in the European Union (EU) and accounts for a significant amount of energy-related CO_2 emissions (IPCC, 2013; The European Parliament and the Council of the European Union, 2010). These statistics are also representative for Norway, according to a report by Multiconsult, SINTEF Byggforsk and NTNU (2009). To the writer’s knowledge, several different organs, international as well as national ones, see the urgency of implementing immediate measures in order to reduce greenhouse gas emissions and the energy consumption in the building sector. The main suggestion is to increase the use of renewable energy sources and improving energy efficiency (IPCC, 2013, 2014; Miljøverndepartementet, 2012; The European Parliament and the Council of the European Union, 2010). A more energy-efficient Europe will contribute to reducing the primary energy consumption and energy imports as well as increasing economic growth and creating new jobs related to energy efficiency (The European Parliament and the Council of the European Union, 2012).

In order to reduce the total energy consumption in the dwelling sector, renovation will be a significant contributor. The energy efficiency directive proposes to renovate 3 % of the heated floor area of all buildings over 500 m^2 occupied by its central government before July 9th, 2015, and buildings over 250 m^2 after this date (The European Parliament and the Council of the European Union, 2012). As of today, the share of renovated buildings is substantially lower than 3 % and hence, gaining knowledge of the dynamics of a dwelling stock will be of great importance in the years ahead.

It is not intuitive to write about how the Norwegian dwelling stock will develop in a realistic manner. Among the many aspects influencing the dynamics, two worth mentioning are political decisions from the EU and Norway.

So far, EU leaders have defined the future energy and climate policy towards 2050 with "The 2020 package", "The 2030 framework" and the "2050 roadmap" (The European Union). The 20-20-20 targets, made by the UN Framework Convention on Climate Change (the "Climate Convention") were a result of the 2020 package. Last year, in October 2014, EU leaders agreed on implementing the 2030 framework. The 2050 roadmap's objective is to create a low carbon society in the EU. The targets for the EU climate and policies are as follows (The European Commission):

Table 1: Overview of the EU climate and energy policies up to 2050 (The European Commission)

The 2020 Package	The 2030 Framework	The 2050 Roadmap
Reducing greenhouse gas emissions by at least 20 % below the 1990 level	Reducing greenhouse gas emissions by at least 40 % below the 1990 level	EU should cut its emissions to 80 % below 1990 levels. →Results in two milestones:
Ensuring that 20 % of energy consumed within the EU comes from renewable sources	Increasing the share of renewable energy to at least 27 % of energy consumed within the EU	By 2030 EU should cut its emissions to 40 % below 1990 levels
Reducing primary energy use by 20 % with projected levels – to be achieved through energy efficiency	Increasing energy efficiency by at least 27 %	By 2040 EU should cut its emissions to 60 % below 1990 levels

Considering that energy consumption from buildings represents such a significant part of the total energy use in the EU, it is realistic that the EU will influence the renovation strategies in the years to come. Upgrading the energy state of dwellings will most likely reduce the operational energy costs, utilize more renewable energy as well as being resource-saving compared to building new dwellings.

Primary energy consumption is a key indicator that is the main reason behind developing the framework conditions in energy system withini the EU, by influencing the energy mix in the EU and reducing the energy import, states industry counsellor in renewable energy, Dag Roar Chrsistensen (Energi Norge, 2012). Primary energy is defined as energy in its pure form, which has not yet been transformed or converted.

In a report, Adapt Consulting (2012), presents the background for the use of primary energy factors in different countries and the consequences of applying different methodologies. Their main findings confirm that there is no unique methodology in European regulations when defining the primary energy in buildings and hence, it is not useful to use primary energy factors when calculating total energy if the objective is to reduce the energy use in a society (Adapt Consulting, 2012; Energi Norge, 2012).

This may become a problem in the future, with an increasing focus upon life cycle assessment for energy systems and energy performance of buildings, combined with an increasing share of renewable energy in the energy mix and more possibilities of importing energy from other countries. When there is no unique calculation method, the primary energy factors used for heating sources, such as gas or electricity, may be quite different dependent on the country and hence influence the calculated primary energy when assessing building audits (Adapt Consulting, 2012; Molenbroek, 2011).

In a study by Building Performance Institute Europe, BPIE (2011), the authors have recommended several policy recommendations in order to achieve the EU's CO_2 reduction targets. The recommendations include, among other, mapping the energy performance of buildings on a national level, providing an easily available data collection and establishing innovative funding alternatives, which provide flexibility and extra funding for household refurbishing. In addition, they suggest changing the existing legislation at EU level from voluntary to binding energy measures. Every country should in addition have a detailed renovation plan and sufficient information about regulations and climate reduction targets. Proper training and education in the construction sector is also mentioned as an important policy recommendation. It is highly sought-after to increase the knowledge of energy-efficient buildings and encourage technological development and competitiveness in the industry (BPIE, 2011).

2.1.2 Norway's climate obligations

Norway has strong ties to Europe for historic and cultural reasons, in addition to sharing values concerning climate policy, human rights and rule of law with the EU. This was an incentive for Norway to enter the Agreement on the European Economic Area (known as the EEA agreement) in 1992. Retrospectively, Norway has taken the initiative to extend their cooperation and agreements to the EU in other areas not concerning the EEA framework, including climate and energy policies (Norwegian Ministry of Foreign Affairs, 2012). At the same time, environmental legislations have indirectly been included by the EU in the EEA agreement. According to the Norwegian Ministry of Foreign Affairs, Norway has a big interest in participating in the development of the EU climate policy. This is for instance shown in a report by KrD (2010), where the main suggestion to solve the energy and GHG issues related to buildings is the same as EU's third 20-20-20 target. KrD manages the National Office of Building Technology and Administration and the Norwegian National Housing Bank as well as policy instruments made by these agencies.

During the last six months, the greener political parties, like Venstre and KrF, have put pressure on the rest of the government to follow EU climate policies, with a 40 % reduction of emissions within 2030 compared to 1990 emission levels. According to Statistics Norway and the Norwegian Environment Agency, the amount of greenhouse gas emissions (GHG) in 1990 constituted about 52 million tonnes CO_2 eq. (The Norwegian Environment Agency, 2015). February 4th this year the current government agreed on this goal and hereby proposes to reduce the emissions in Europe, together with the EU, by 40 %, or by about 21 million tonnes CO_2 eq.

However, it is still uncertain to what extent Norway will reduce its national emissions. Editor of economics in Aftenposten, Ola Storeng, states that Norway is a country where it is challenging to do climate politics, due to our big oil and gas production on the one hand and Norway's green electricity production, representing the national energy system, on the other hand (Aftenposten morgen 5. februar, 2015). The electricity comes from hydropower, which is a renewable energy source. In that manner, the power provided to Norwegian homes is environmentally friendly and fulfills climate ambitions many countries seek to have reached within 30 years.

The challenging part of executing climate policies in Norway is the economy. It is more expensive to cut down emissions by reducing the oil and gas production rather than helping out other countries cutting down their emissions. This is one of the reasons why Norway has paid for UN-certified energy measures in industrial countries as an alternative to cutting down their own emissions. A change from previous climate policy in Norway is that the opportunity to "ransom oneself" will not be possible anymore. From now on, the climate targets are to be reached in the respective countries only and there will not be an opportunity to use climate quotas from developed countries. Time will show if there will be a new international climate agreement in Paris in December 2015. One potential effect of several countries coming together to discuss climate policies, is that they may set stricter conditions for the consumers and the industry than what they would have done individually. (Aftenposten morgen 5. februar, 2015).

In Europe, the Energy Performance of Buildings Directive (2008) has given the standard EN 13790:2008 as a guideline to assess an energy audit for a building. In Norway, the same standard applies.

However, Standard Norge (2014) has written a Norwegian standard, adjusted to Norwegian conditions in NS 3031:2014. The calculation methods for energy audits of buildings are:

- Simple spreadsheet models (NS3031:1987)
- Seasonal and stationary methods on a monthly basis (NS3031:2014)
- Dynamic calculation programs based on an electrical circuit analogy, RC (SIMIEN, ISO 13790)
- Advanced dynamic programs based on difference methods (IDA-ICE, ESP-r)
- Other advanced simulation programs (Computational Fluent dynamics (CFD), Earth energy designer (EED))

2.2 The Norwegian dwelling stock

2.2.1 The historical development and current situation

"A dwelling is a unit of property which contains one or several rooms, is built or rebuilt as a whole season private residence for one or several persons, has its own access without having to go through another dwelling. Dwellings may be studio apartments and apartments. An apartment is a dwelling with minimum one room and a kitchen. A studio apartment is a room with its own access designed for one or several persons, has access to water and a toilet without having to go through another dwelling" (SSB, 2013).

Thanks to frequent housing censuses in Norway, it has been possible to make statistics of the dwelling development in Norway. The number of constructed and completed dwellings has varied a lot over the years.

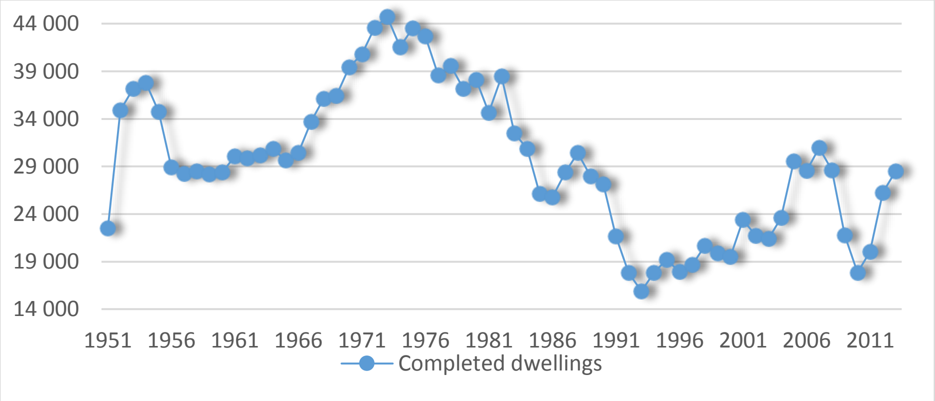


Figure 2: The Norwegian dwelling stock development from 1951 to 2013. Completed dwellings (SSB, building statistics)

See Figure 2 for an overview of completed dwellings in the timespan 1951 to 2013. As shown in the graph, there was a “building boom” in the early 70s, when almost 45,000 dwellings were completed per year. In contrast, the number of completed dwellings was less than 20,000 per year in the early 90s.

The “construction boom” of the 70s was due to the big focus of the government at that time on creating housing after the Second World War in order to solve the housing shortage. The Minister of Local Government at that time, Helge Seip, presented these plans of increasing the housing construction on a gigantic scale and managed to execute them over a short period of time when housing shortage was still a problem (Norsk biografisk leksikon; Prognosesenteret & Entelligens, 2011).

Since the 1980s, housing construction has been less controlled by the government and has instead reflected the actual dwelling demand. Hence, housing construction has followed the fluctuations of the market to a greater extent (Prognosesenteret & Entelligens, 2011). SSB presents the Norwegian dwelling stock of 2012, where dwellings built before 1990 represent approximately 80% of the total number of occupied dwellings. See Table 2 below for a presentation of the Norwegian residential stock in number of occupied dwellings and useful floor area (BRA).

Table 2: SSB: The Norwegian dwelling stock divided by dwelling types and construction year in number of dwellings and user space (Brattebø & O'Born, 2014).

Construction period	Number of occupied dwellings				BRA (1000 m^2)			
	SFH	TH	AB	Total	SFH	TH	AB	Total
Before 1961	414,980	156,762	195,187	766,929	56,073	11,885	16,211	84,169
1961 -1970	153,019	48,413	74,541	275,973	20,505	5,025	4,842	30,371
1971-1980	206,011	69,807	84,424	360,242	29,254	7,430	6,337	43,020
1981-1990	192,422	67,112	51,144	310,678	32,712	7,093	4,149	43,953
1991-2001	113,711	58,248	63,552	235,511	17,170	5,619	4,673	27,462
2002-2012	86,578	62,383	106,897	255,858	13,073	5,985	7,932	26,991
Total	1,166,721	462,725	575,745	2,205,191	168,786	47,362	41,585	257,733

Dwelling style trends

There have been several building style trends for dwellings throughout the decays after the Second World War. According to Sørby (1992), the first years after the Second World War were strongly influenced by a simple and level-headed architectural style, where the typical dwellings were single-family houses with saddle roof. Many of the of the dwellings were built with light frame walls, and from the middle of the 50s, it started to become more normal to use insulation in the outer walls in combination with light frame-built walls, even though the insulation standards during this time cohort were limited. The 60s were more influenced by modernism and flat roofs, stained brown and with a basement. The 70s building style was more influenced by structuralism and prefabricated houses which were similar (Ramstad, 2006; SINTEF Fag, 2014b; Sørby, 1992).

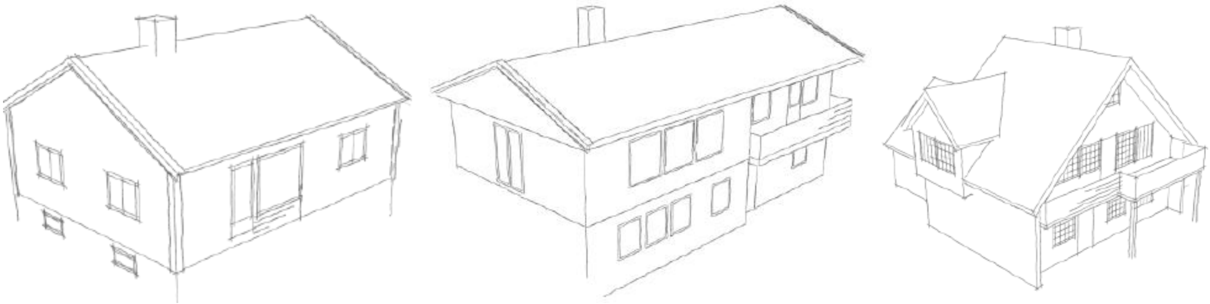


Figure 3: Norwegian example buildings from (left to right) the 60s, 70s and 80s

2.2.2 The current energy need and typical heating sources

Prognosesenteret and Entelligens have done a thorough study calculating the national energy consumption of the Norwegian dwelling stock in 2010. The annual energy consumption of the Norwegian dwelling stock is estimated to 45.2 TWh. The result is similar to SSB's statistics on the same topic, concluding with an energy demand for Norwegian dwellings of 43.7 Twh (SSB, 2014b). One of the reasons for SSB having a discrepancy of more than 3 % may be that SSB's study is based on consumer studies and these samples may give less reliable raw data concerning the dwelling stock classification. Prognosesenteret and Entelligens, however, have based their model on stereotypical dwellings and not average dwellings. For instance, they have operated with an integer number of floors for the standard dwellings and not a decimal number (Prognosesenteret & Entelligens, 2011). Hence, there is uncertainty regarding the results of energy use for the Norwegian dwelling stock associated with both of these sources.

There are several factors influencing the energy use in a dwelling stock. Dwelling type, energy carrier and year of construction are just three out of many variables. Prognosesenteret states that the most significant variable out of the three factors mentioned concerning energy use, is the dwelling type. The dwelling type characteristics describe the size of the dwelling and the main construction material of the building envelope. Both of these characteristics influence specific energy need for heating [kWh / m^2]. Furthermore, the floor space influences the heating demand directly. The larger the dwelling, the more energy is needed. Another correlation is that the specific energy need decreases when the building gets more compact in terms of containing more dwellings per floor. Hence, apartment blocks (AB) have a lower energy need than single-family houses (SFH) (see Figure 4). The construction material influences the energy need indirectly by having thermal characteristics which further influence the specific energy need (Prognosesenteret & Entelligens, 2011).

Average energy consumption for Norwegian households depends on dwelling type and heat source, as illustrated in Figure 4. Farmhouses and SFH have a bigger heat loss than terraced houses (TH) and apartment blocks (AB) and this may explain why they have a higher energy consumption. The significant heat loss from SFH and Farmhouses are, among others, due to a larger floor area, a high volume compared to the thermal envelope and their choices in energy carriers for heating purposes. SFH and farmhouses use firewood for heating to a much higher extent than TH and AB. Due to firewood having an efficiency degree that is 25 % lower than electricity, SFH and farmhouses have to use more energy in order to deliver the same amount of heat as dwellings using electricity as energy carrier. Farmhouses and the SFH may be considered the same dwelling type due to similar size, construction material and energy carriers (Prognosesenteret & Entelligens, 2011).

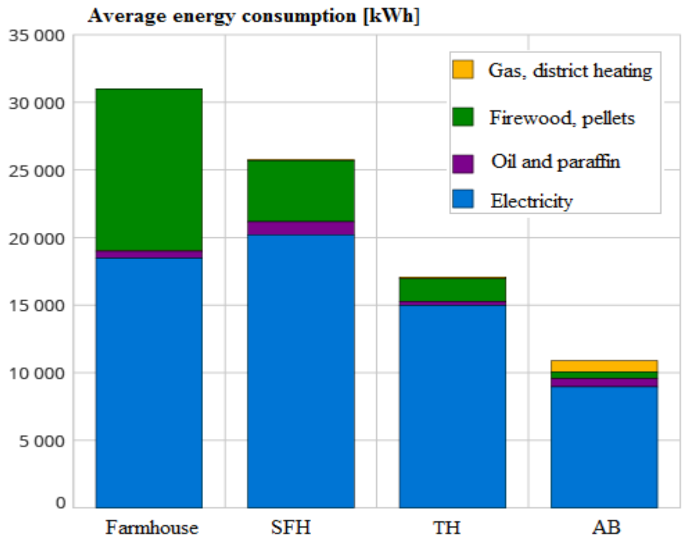


Figure 4: Average energy consumption per household for different dwelling types in 2012. Reproduced (SSB, 2014b)

2.2.3 Space heating variables

There are many important variables influencing the energy balance of a building. The next sub chapter will review the insecurity of energy use in buildings related to indoor temperature and infiltration.

Indoor temperature

Prognosesenteret states that there has been done little research on the average difference in indoor and outdoor temperature despite this being a vital variable influencing the energy balance of a building (Prognosesenteret & Entelligens, 2011). There exists good statistical data from outdoor climate conditions, so the unreliable parameter is the indoor set-point temperature. In NS 3031:2014 (Standard Norge, 2014) it is decided to put an average indoor temperature of 20.33°C as the set-point temperature used in dwellings when calculating the energy need. (20.33°C is the weighted average of 19°C for 8 hours and 21°C for 16 hours per 24 hours.) However, the representative indoor temperature may vary. Entelligens AS has conducted energy audits for approximately 100 dwellings and found that the average temperature for a standard residential building is substantially lower than 20.33°C. The average indoor temperature ranged from 18.0 °C – 20.4 °C for single-family houses, from 18.9 °C – 20.9 °C for terrace houses and from 20.2 °C – 22.0 °C for apartment blocks. If energy calculations are based on a higher indoor temperature than what occurs in reality, the calculated energy need of the dwelling will be substantially higher than the real energy need. In addition, it may be difficult, particularly for older dwellings, to maintain desired indoor temperature and avoid unnecessary heat loss (Prognosesenteret & Entelligens, 2011).

The share of heated area is bigger in apartment blocks than terrace houses and single-family houses. This is due to TH and SFH representing bigger dwellings and there are often unused rooms that are not heated directly.

In order to show how much the indoor temperature may influence a building's energy need for heating, Prognosesenteret has done a sensitivity analysis of the indoor temperature. As shown, there is an almost linear correlation between the indoor temperature and the heating demand of the dwelling, see Figure 5.

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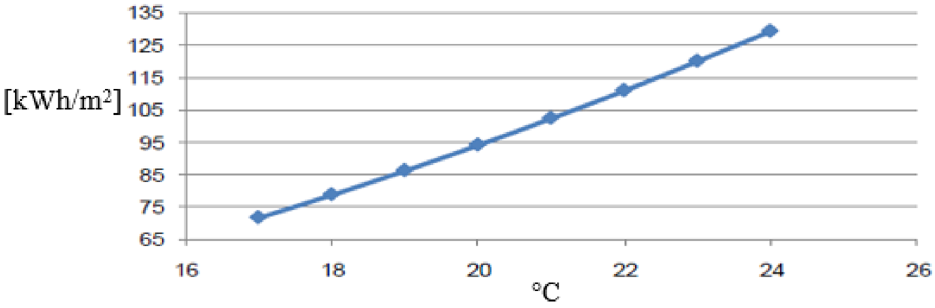


Figure 5: Indoor temperature versus heating demand [kWh/m^2].
Reproduced (Prognosesenteret & Entelligens, 2011).

Ventilation heat loss

The energy demand of the dwelling is highly sensitive to the parameters influencing the infiltration and ventilation of a dwelling. Below, Figure 6 shows the energy need increase with an increase in the air leakage rate. The air leakage rate measures the infiltration at a reference pressure of 50 Pascal. The example is from the dwelling stock segment SFH 1971 – 1980 in Prognosesenteret & Entelligens (2011). However, the relationship between the air leakage rate and the heating need is representative for all dwelling stock segments.

Prognosesenteret and Entelliengs (2011) have presented an overview of typical values for air leakage rate and natural air change rates for different dwelling stock segments (see Table 3). As shown, there is huge variation between the air leakage rates. Furthermore, there is no linear relationship between the air leakage rate and the natural air change rate of the dwelling.

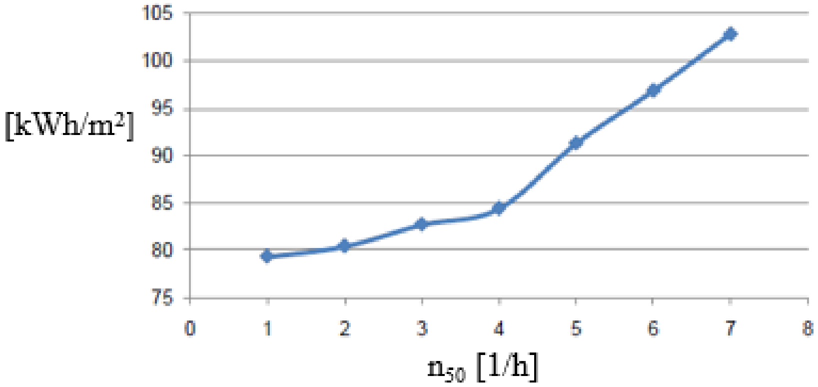


Figure 6: Air leakage rate, n_{50} [1/h] versrus heating demand [kWh/m^2].
Reproduced (Prognosesenteret & Entelligens, 2011).

Table 3: Air leakage rate and air change rate in different dwelling types (Prognosesenteret & Entelligens, 2011)

Standard dwelling	Air leakage rate n_{50}	Air change rate n_{inf}
SFH		
Before 1956	5	0.6
1956 – 1970	5	0.5
1971 – 1980	4	0.4
1981 – 1990	4	0.4
1991 – 2000	3.5	0.4
2001 - 2010	3	0.8
2011 - 2020	2.5	1.2
AB		
Before 1956	5	0.5
1956 – 1970	5	0.2
1971 – 1980	3	0.3
1981 – 1990	1.5	0.4
1991 – 2000	1.5	0.4
2001 - 2010	1.5	1.2
2011 - 2020	1.5	1.7
TH		
Before 1956	5	0.5
1956 – 1970	5	0.5
1971 – 1980	4	0.4
1981 – 1990	4	0.4
1991 – 2000	3	0.4
2001 - 2010	3	0.8
2011 - 2020	2.5	1.2

2.2.4 Renovation activities

IPCC states that one of the most cost efficient climate measures today is renovation in the building sector (2013). Historically speaking, the Norwegian dwelling stock represents one of the most renovated dwelling stocks in the world due to a strong economy. A decent share of the total renovation investment is energy related. In 2010, about 10 billion NOK was spent on energy renovation for the 2.3 million Norwegian dwellings. This is about 20 % of the total renovation investment that year (Prognosesenteret & Entelligens, 2011; Risholt, 2013) Most likely, this renovation trend will not change, but rather increase in the years to come, due to today's renovation incentives and assumed future renovation incentives (Risholt, 2013).

Even though the renovation expenses on Norwegian dwellings has increased over the last decade, there are still many dwellings which have the original technical standard as when they were built. Table 4 presents the percentage of dwellings in the dwelling stock being either refurbished or in their original state (Prognosesenteret & Entelligens, 2011).

Table 4: Share of dwellings in the Norwegian dwelling stock refurbished. Reproduced (Prognosesenteret & Entelligens, 2011).

	Original dwelling	Refurbished	Changed windows	Insulation of walls	Insulation of ceiling/floor
SFH					
Before 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 %
TH					
Before 1956	14 %	86 %	71 %	60 %	45 %
1956 – 1970	22 %	78 %	68 %	30 %	38 %
1971 – 1980	39 %	61 %	56 %	12 %	20 %
1981 – 1990	91 %	9 %	5 %	0 %	8 %
1991 – 2000	97 %	3 %	3 %	0 %	0 %
2001-2010	100 %	0 %	0 %	0 %	0 %
AB					
Before 1956	16 %	84 %	73 %	43 %	35 %
1956 – 1970	25 %	75 %	66 %	37 %	29 %
1971 – 1980	29 %	71 %	67 %	24 %	6 %
1981 – 1990	91 %	9 %	7 %	5 %	6 %
1991 – 2000	97 %	3 %	3 %	3 %	0 %
2001-2010	100 %	0 %	0 %	0 %	0 %

It is shown in the table above that most of the dwellings built before 1971 have gone through one or several refurbishment measures. Among the younger dwellings, built after 1990, it is the other way around, with less than 5 % of dwellings being subjected to refurbishment and a change of the dwelling's technical standard. In the report "Energiplan – tre trinn for tre poker" by Sintef Fag, it is pointed out that there is a huge energy upgrade potential among the SFH built in the 70s and 80s due to the fact that only 6 % and 3 % of these have added newer insulation to the outer walls (SINTEF Fag, 2014b). This statement is supported by the potential and barrier study from Enova, which sets the average lifetime for passive energy measures at 30 years. Passive energy measures are energy measures indirectly influencing the energy performance of the building, such as upgrade of the building envelope (Prognosesenteret & Entelligens, 2011).

2.2.5 Energy behavior and barriers

Climate and environmental topics are so-called low engagement topics with a high social status value and few people will admit that they are not concerned about the environment (Prognosesenteret & Entelligens, 2011). According to Risholt (2013), there are no previous studies on how these barriers influence the renovation activity for Norwegian single-family houses. Prognosesenteret has, however, extended the EU project BARENERGY's ("Barriers for energy changes among consumers and households") classification of different barriers and mapped the following categories of barriers in energy changes in Figure 7 below.

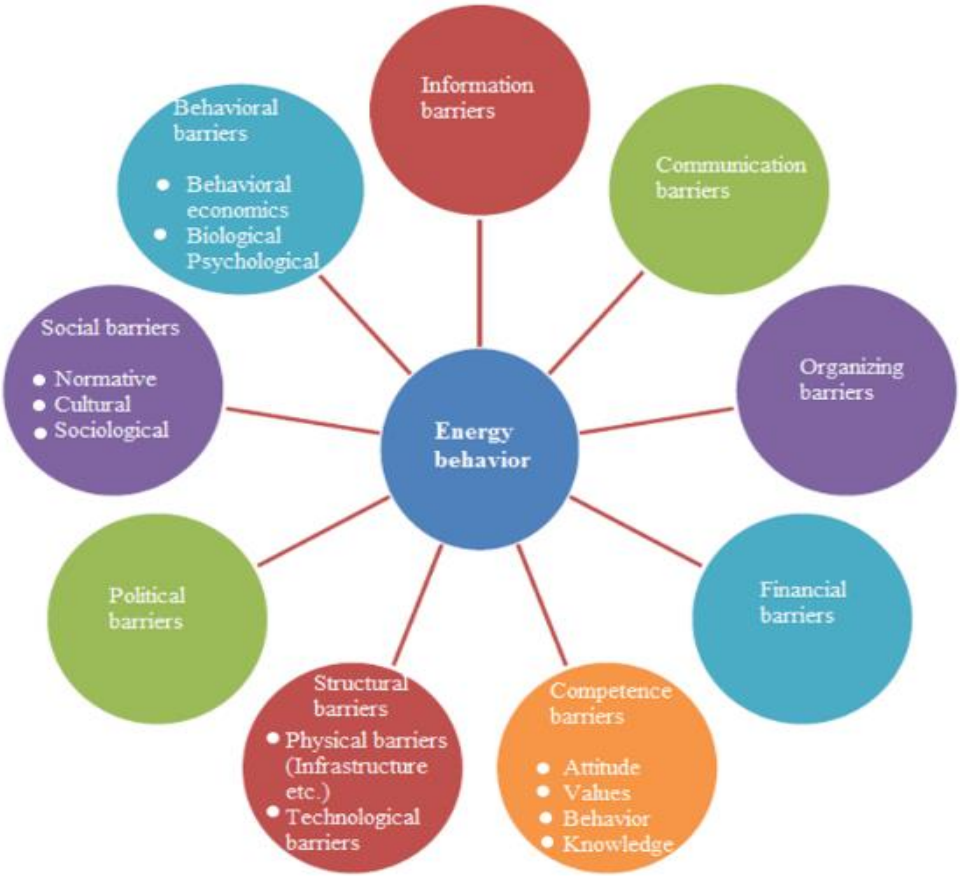


Figure 7: Barriers for energy changes among consumers and households. Reproduced (Prognosesenteret & Entelligens, 2011).

They did a survey, asking people about the main reasons for refurbishing windows and adding insulation to a Norwegian household. According to the survey, the main reason for insulating the dwelling was to save energy and adding it as an extra measure to the main refurbishment.

The main reasons for changing the windows, on the other hand, was necessity, in addition to it being an extra measure to the main refurbishment. Hence, refurbishing windows as an energy saving measure was considered a secondary reason (Prognosesenteret & Entelligens, 2011).

In a study by Building Performance Institute Europe, BPIE (2011), it is stated that the financial barrier for investing in energy saving measures in buildings was the biggest. Among other reasons, lack of knowledge and services and the lack of attractive products in the market are significant barriers according to Risholt (2013). Lack of knowledge means in this context that the homeowners do not know the benefits nor possibilities related to energy efficiency at home. There is neither a big market for services, or the knowledge on how to provide the services among craftsmen related to energy efficiency (Risholt, 2013).

Another important perspective is that despite the fact that it is technically possible and that there is a huge energy potential in the dwelling sector, it is not always economically reasonable to spend resources on breaking the barriers down (Enova, 2012).

2.2.6 Renovation upgrade to TEK and passive house standard

Single-family houses built before 1990 represent a large part of today's dwelling stock. Due to more strict requirements over the last couple of decades, concerning the building envelope and technical systems, these dwellings are less energy efficient compared to dwellings that are built today. One example is the change in U-value requirements for wooden frame walls built between 1945 and 2010 (Risholt, 2013), that is a measure on the heat loss through the building envelope. The majority of the single-family houses built in this time period have a wooden exterior cladding and are insulated with mineral wool (Risholt, 2013; SINTEF Fag, 2014b).

Table 5: U-value requirements and insulation thicknesses for wood frame walls built between 1945 and 2010. Reproduced (Sintef building and infrastructure, 2010, Risholt, 2013).

Building period	1945-1960	1960-1980	1980-1997	1997-2007	2007-
Insulation materials	Air	Mineral wool	Mineral wool	Mineral wool	Mineral wool
Insulation thickness [mm]	-	100	150	200	250
U-value [W/m^{2}K]	1.5	0.5	0.29	0.22	0.18

As shown in Table 5, there is a huge renovation upgrade potential for wooden frame dwellings built before 1980, due to substantially lower U-value requirements than the current, which is 0.18 W/m2K (National Office of Building Technology and Administration, 2010). There are many ways to upgrade the building envelope. One approach is to have a stepwise energy upgrade, renovating the building envelope in three main steps. This will in total improve the dwelling's energy state to an ambitious level, corresponding to today's regulation requirements or better.

In the report by Sintef Fag (2014b), an energy plan is presented of stepwise refurbished single-family houses built between 1960 and 1990, upgrading the dwellings to TEK 10, passive house level or low-energy level. The steps are followed in an order that will prevent an energy lock-in and distribute the total investment costs over a longer time span. An energy lock-in means that the energy efficiency potential decreases due to unnecessary refurbishing in the prior renovation steps. The objective of the report by SINTEF Fag (2014b) is to create a stepwise energy plan that will upgrade the building envelope to an ambitious level, which is executed and correlated to the next renovation step. The steps include renovation of outer walls, cellar (floor and walls bordering the terrain) and ceiling, in addition to technical measures (SINTEF Fag, 2014b).

One alternative to getting a discount on the renovation costs is to apply for support by Enova. In 2013, Enova introduced an upgrade support at their webpage, www.enova.no, if the following criteria of the dwelling are fulfilled:

- The energy supply must have an energy performance certificate better than red. Hence, the dwelling must have an energy mix avoiding pure electricity or fossile fuels.
- Fulfill the energy need requirements in accordance to the table presented on the webpage (Enova)
- Reduce the heat loss coefficient by 30 % and not exceed the requirements to the heat loss coefficient presented on the webpage (Enova)

2.2.7 Insulation of outer walls

Upgrading the dwelling façade and insulating the outer walls may be an efficient renovation measure that will improve the airtightness of the dwelling's thermal envelope and hence be energy saving due to a lower infiltration. Throughout time, the main construction materials for Norwegian houses have been split into two, where single-family houses and terraced houses mostly have been wood based and apartment blocks built out of concrete. According to Ramstad (2006), wood-based dwellings represented more than 98 % of the Norwegian dwelling stock. Newer statistics, however, show that there are dwellings which are made out of other construction materials, like steel and LECA (light expanded clay aggregate concrete). Below Table 6 shows the share of main construction materials for Norwegian dwellings.

Table 6: Main construction materials for Norwegian dwellings. Reproduced (Prognosesenteret & Entelligens, 2011)

Main construction material	Wood	Concrete	LECA	Steel / other
SFH	83 %	7 %	7 %	2 %
TH	78 %	11 %	5 %	6 %
AB	23 %	54 %	1 %	22 %

Even though many new dwellings and dwellings built in the future will be based on other construction materials, most of the dwellings in the Norwegian dwelling stock consist of older dwellings. Hence, there is reason to state that most single-family houses and terraced houses are wood based and that a large share of apartment blocks are made out of concrete.

Insulation methods

In the Norwegian building sector, there are three main insulation methods when insulating the outer wall of a building: insufflation of insulation and exterior and interior wall insulation. Insulation of outer walls has the intention of reducing the heat loss from the outer walls and making the walls more damp proof (Sintef Byggforsk, 2004).

Exterior wall insulation is a well-known method where one applies new thermal insulation on the outside of the wall. This is the most common wall insulation method. The additional thermal insulation will cover the original wall, a coherent layer covering the total wall height, eliminating the thermal bridges and making the construction warmer and hence drier (Sintef Byggforsk, 2004).

Interior wall insulation aims at adding new thermal insulation from the inner walls. This is only relevant if the residence coating is intact and in a good state. Unfortunately, there seems to be more disadvantages of adding new insulation from the inner rather than from the outer walls. The heated floor area will be reduced, and in contrast to the exterior insulation technique, it will not be possible to avoid the thermal bridges due to interior walls and timberwork. In addition, electrical installations and anything else installed along the walls must be removed during the renovation (Sintef Byggforsk, 2004).

Insufflation of thermal insulation are well suited in half-timbered walls with cavities. It is possible to insufflate the insulation from the interior or exterior walls. However, the cavities should have a thickness of 50 mm or less. It is possible to combine insufflation of thermal insulation with interior or exterior wall insulation (Sintef Byggforsk, 2004).

In the stepwise energy upgrade report, it is advised to consider installing a balanced ventilation system when insulating the outer walls, in order to remove moist air and increase the air exchange rate so that the indoor air quality is maintained (SINTEF Fag, 2014b).

Insulation materials, energy consumption and greenhouse gas emissions

Both by national as well as international organs, energy efficiency is considered the most important climate measure in order to reduce the greenhouse gas emissions and energy consumption in the building sector (IPCC, 2013; KrD, 2010). Energy efficiency often requires a higher consumption of materials, and especially an increase of insulation materials. A higher material consumption results in a higher bond energy and bond greenhouse gas emissions from the materials (Shrestha, 2014). It is therefore important to look into the choice of insulation materials in addition to the actual energy efficiency measures (Korjenic, 2011). In a study by Sørnes and Kristjansdottir (2012), an LCA is performed for different wood-based outer-wall constructions. The climate accounts in the study show that the insulation material emits the most compared to other outer wall components.

The report "Energi og klimagassanalyse av isolasjonsmaterialer" by SINTEF Fag presents a life cycle from cradle to construction site assessment of insulation materials in outer walls in Norwegian households. They compare the materials concerning energy need, greenhouse gas emissions and hazardous compounds. The conclusion of the study is that insulation materials that are based on mineral wool use far less energy and emit less greenhouse gas than XPS, EPS and vacuum insulation panels (VIP). Mineral wool is the most common insulation material in Norwegian dwellings (SINTEF Fag, 2014a).

The results from the insulation material study are presented in Figure 8 and Figure 9. In order to compare the insulation types, they are of the same functional unit of 1 m^2 thermal insulation with a thickness giving the thermal resistance R = 1 m^2K/W.

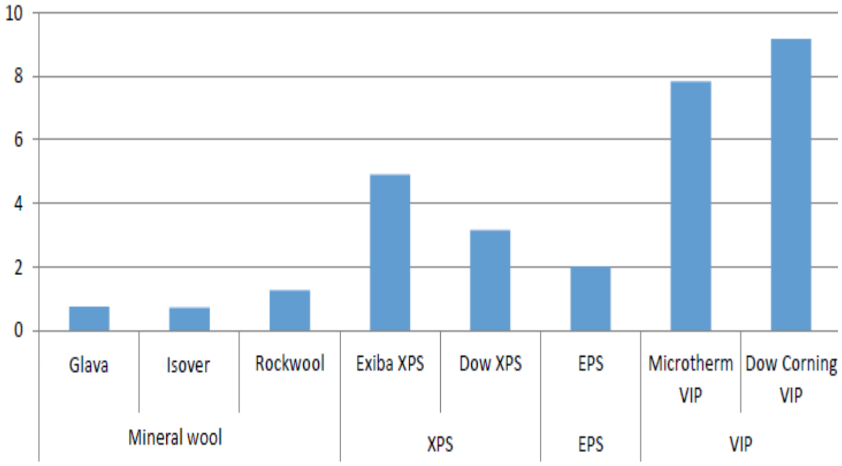


Figure 8: CO_2 emissions from cradle to construction site [kg CO_2 eq.]

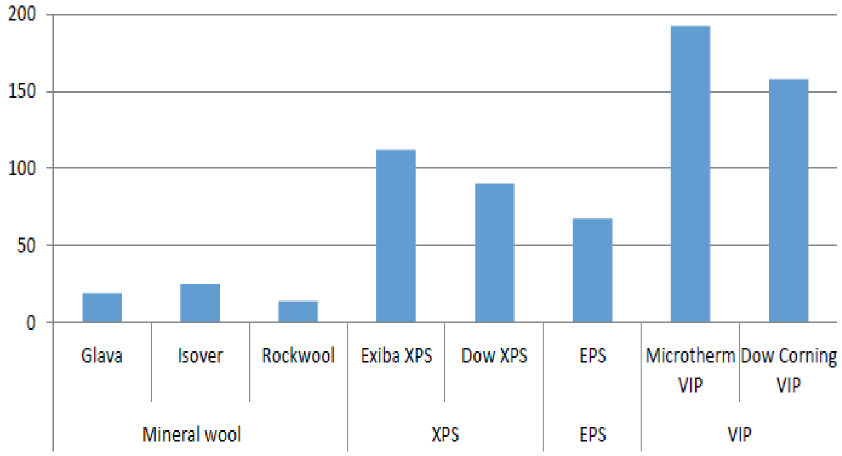


Figure 9: Energy consumption from cradle to construction site [MJ]

Even though the VIP materials emit far more CO_2 and consume more energy than the other insulation types, it is concluded in the study that insulating the outer walls to passive house standard is sufficiently energy saving regardless of the insulation material. A lower energy consumption in the operational face of the dwelling will reduce the direct CO_2 emissions. Hence, it pays off to insulate with VIP rather than not insulating the outer walls (SINTEF Fag, 2014a). However, a perspective of concern is the risk of worsening the thermal characteristics of VIPs. In an article about VIPs in wooden frame wall construction, Haavi and Jelle broach the importance of installing robust VIPs (2012). This is due to the decrease in their thermal characteristics after insulation of the outer walls. Natural ageing of the panels may increase the thermal conductivity between 4mW/mK and 8mW/mK. Nevertheless, if the panels are perforated, for example by a nail, the thermal conductivity may increase up to about 20 mW/mK. This implies that it is crucial to take proper care of vacuum insulation panels in order to maintain the thermal characteristics and hence energy savings from the non-aged VIP condition (Haavi & Jelle, 2012).

2.2.8 Waste from construction, rehabilitation and demolition of buildings

SSB maps the national waste from all sectors. The annual accounts for waste in the building sector are complementing the national waste accounts. In 2000, SSB published a thorough report mapping the waste of different construction materials from renovation, construction and demolition of buildings. Their method was looking at waste generation factors, which are based on empirical data from 131 building projects in Oslo. The factors are adjusted for historical figures from Finnish and Norwegian building projects. See Table 7 below for an overview of the waste [kg / m^2 floor space].

Table 7: Waste from construction, rehabilitation and demolition of Norwegian dwellings. Reproduced (SSB, 2000).

Waste [kg / m^2 floor area]	Total	Insulating material and EPS	Asbestos	Other hazardous waste	Gypsum	Concrete and brick
Construction	34.92	1.2	0.0	0.017	3.5	6.5
Rehabilitation	93.95	0.6	0.5	0.050	5.9	40.4
Demolition	538.27	2.2	2.5	0.567	4.13	387.3

When accumulating the waste production factor with the total amount of constructed, refurbished and demolished buildings in Norway in the year 1998, SSB got the following results for the total amount of waste from different building components:

Table 8: Total waste [tonnes] from construction, rehabilitation and demolition, by component and activity from 1998 (SSB, 2000).

Waste [tonnes]	Total	Construction	Rehabilitation	Demolition
Total	1,542,720	209,489	372,138	961,094
Insulation material and EPS	6,326	3,467	1,891	967
Concrete and brick	1,056,741	77,033	180,939	798,770
Wood	240,725	41,462	122,845	76,418
Metal	42,753	3,187	9,061	30,504
Gypsum	37,088	14,046	20,908	2,133
Glass	4,675	1,015	2,028	1,631
Paper, cardboard and plastics	16,736	7,923	2,385	6,428
Hazardous waste	7,563	112	2,789	4,662
Of this, asbestos	6,335	-	2,535	3,800
Waste with unknown composition	130,115	61,244	29,290	39 581

These numbers represent the waste amount from the building sector in 1998. SSB has not published any newer reports than the one from 2000 about waste from building activities. They have, however, mapped the waste amount from building activities in the recent years, from 2009 to 2012. As shown in Figure 10, the total waste amount from building activities in Norway from 2009 – 2012 clearly exceeds the total waste amount that was calculated in 1998, with a 25 % increase in waste generation in the building sector in 2012 compared to 1998 levels. There is reason to be concerned about waste amounts from construction, rehabilitation and demolition in the building sector, considering a rapidly growing population and increase in dwelling demand.

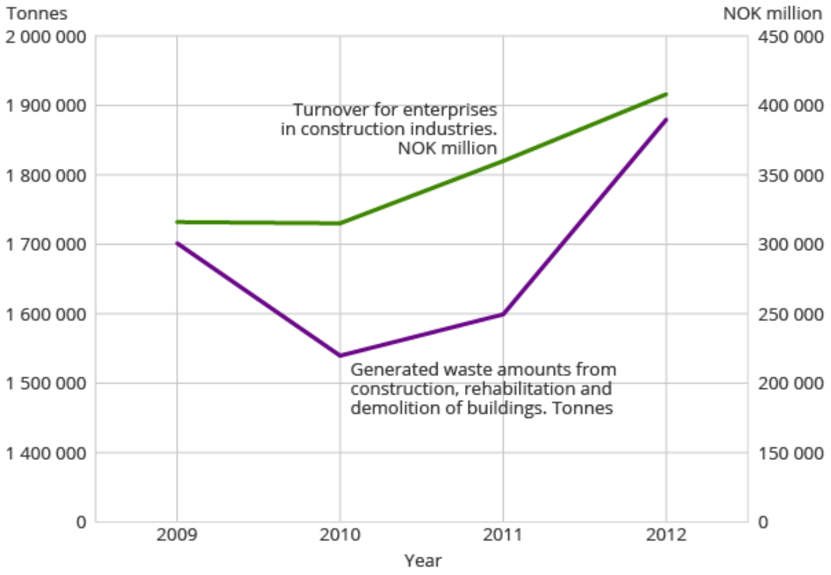


Figure 10: Generated waste from construction, rehabilitation and demolition of buildings and turnover for enterprises in construction industries (SSB, 2014a)

2.3 Literature review of energy audit models and building stock models

The following chapter gives a brief literature review of energy audit models for a single building and building stock models.

2.3.1 Energy balance models

TABULA (Typology Approach for Building Stock Energy Assessment), a project supported and developed by the Intelligent Europe project, is an energy audit model based on the seasonal and stationary method (Institut Wohnen und Umwelt GmbH; Loga & Diefenbach, 2013). The objective of the project was to develop future refurbishment strategies for European households in order to reduce the energy consumption. 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 project, using the same methodology for national building stocks in 16 European countries. Brattebø and O'Born (2014) have developed a typology brochure for Norway’s housing stock, divided into three building types and seven time cohorts for construction. Each building profile in the typology brochure includes two different refurbishment packages in addition to the original state, and their corresponding energy results and data input for each of the 21 example buildings representing their respective dwelling stock segment.

The energy audit model, SIMIEN, is, among others, used in the stepwise energy upgrade study carried out by SINTEF Fag (2014b) on Norwegian single-family houses built in the 1970s. The calculated annual energy need for heating was 199 kWh/m^2 in original state (2014b). Another study using a similar energy audit to SIMIEN is the barrier study by (Prognosesenteret & Entelligens, 2011). They found the annual energy need for heating of a single-family house from the 1970s to be 87.8 kWh/m^2. The heating demand was calculated to be the average for all single-family houses in this time cohort. This includes refurbished houses as well as houses in an original state.

2.3.2 Building stock models

A building stock model is a model giving insight to the flows influencing the building stock or building stock segments over a time period, the development concerning construction demolition and energy use in a building stock.

Among building stock models, one distinguish between the bottom-up (Shorrock & Dunster, 1997) and the top-down approach (Johnston, 2003). Hence, looking into many building types and construction periods or fewer to get a better overview of the total building stock. In addition, one distinguishes between linear and dynamic models, hence modelling with static building stock rates (Lavenergiutvalget, 2009; Prognosesenteret & Entelligens, 2011) and using dynamic stock flows that may change throughout the simulation (Sandberg, Sartori, & Brattebø, 2014b).

The model developed by Sandberg et al. (2014b) measures long-term development in a building stock in addition to flows presenting renovation in the stock. The model methodology is based on studies conducted by Müller (2006), Bergsdal and Brattebø (2007) and Sartori, Bergsdal, Müller, and Brattebø (2008). In the last study (2008), the model divides the building stock into time cohorts and type classes, enabling the user to look into the segments of the building stock instead of the stock as a whole. The building demand is dependent on the number of persons per dwelling and the population. This model looks in addition on the impact on energy use and CO_2 emissions, and therefore has an additional separate flow in the system called renovation activity. Several renovation alternatives of different "depths" may apply in the model, where the different renovation alternatives correspond to different energy balances.

Results from Sandberg et al.'s model (2014a) show that by renovating the Norwegian housing stock in 40-year cycles, the stock is expected to have a renovation rate that will increase from 1 % today to 1.5 % in 2050 . The energy efficiency directive proposes a renovation rate of 3 % for public buildings occupied by central government by 2030 (The European Parliament and the

Council of the European Union, 2012). Hence, according to Sandberg's studies (2014a), this target is not likely to be reached in Norway within the first decades. Further, the most critical contributor to the total energy need in the residential stock is space heating, representing about 50 % of the total energy usage. The rest origins from technical appliances, water hating and upstream energy flows (Sandberg & Brattebø, 2012). Sensitivity analysis of Sandberg's model (2014a) concludes that that the model is robust to changes in input parameters.

In the report "Europe's buildings under the microscope", a study is carried out of the energy potential of a building stock from today (2010) up to 2050, looking into energy use and CO_2 emissions of different rates and types of renovation. Europe 27, Norway and Switzerland were the countries participating in the study. The country-by-country study utilizes a methodology of static stock and renovation rates, which is in line with a previous study on energy savings potential in EU member states, candidate countries and EEA countries (BPIE, 2011; Eichhammer, Fleiter, & Schlomann, 2009). The building stock model uses constant rates for demolition and construction of respectively 0.2 % and 0.5 % and a baseline renovation rate of 1 % (BPIE, 2011).

Prognosesenteret and Entelligens have constructed a model of the Norwegian dwelling stock, investigating how much energy which is potentially saved by renovating the historic dwelling stock to TEK 10 standard. They used example buildings divided into different types and age cohorts, reflecting the Norwegian dwelling stock Standard Norge (2014). In order to get the total energy need of the building stock, the energy results from one building was scaled up to the number of dwellings representing the building type. In addition, the model is based on static stock rates, with rates for demolition of 0.3 % and the dwelling stock demand being dependent on persons per dwelling and a baseline population forecast. The technical energy efficiency potential of the Norwegian dwelling stock was estimated to be 13.4 TWh, where every household could save more than 6,000 kWh on an annual basis. The energy potential represents approximately 30 % of the total energy that was delivered to Norwegian households in 2010. This constitutes a 30 % reduction of the energy use by utilizing available technology and expertise in Norway (Prognosesenteret & Entelligens, 2011). Other studies supporting that there is a huge theoretical energy potential in the Norwegian dwelling stock are Arnstadutvalget (2010), Lavenergiutvalget (2009) and the IEA-SHC task 37 report (Thyholt, 2009). In several of the potential studies, the theoretical results show that the biggest energy potential is among single-family houses due the large share they represent in the Norwegian housing stock. Hence, these houses will be in need of comprehensive refurbishment in the next couple of decades.

Thyholt (2009) found that by implementing energy measures on the building envelope and improve the technology for the heating system, the energy need in the current Norwegian residential stock could be reduced by 25 - 40 %.

An argument for not using static flow rates for demolition influencing the dwelling demand in the housing stock, as for example Prognosesenteret & Entelligens (2011), is that the stock demand, and hence, the stock composition is not likely to stay unchanged over decades. When a model measures the energy use of the stock, the results will be based on the existing energy demand of the building stock rather than the forecasted one (Sandberg et al., 2014b).

3. Methodology

The following chapter will give a presentation of the models applied in this master's thesis work, a presentation of key input parameters used in the models, in addition to a review of the scenarios utilized in the scenario analysis. See appendix 2 for equations and parameters used in calculations.

3.1 Analytical methods

3.1.1 Conceptual outline

The work is divided into two parts. Part 1 is to assess the energy performance of -1- typical single-family building constructed in the 1970s when applying different insulation solutions to the building façade. This includes evaluating the primary energy, delivered energy and operational CO_2 emissions of the building. In addition, I will do a material analysis of the insulation materials used when refurbishing the outer walls. See Figure 11 for a presentation of the KPI values in the material analysis. Part 2 includes an evaluation of the energy savings and CO_2 reduction potential of the total stock of single-family houses in the Norwegian dwelling stock when applying different insulation solutions to the façade, when using the currently developed dynamic segmented building stock model by Sandberg and Sartori (2015).

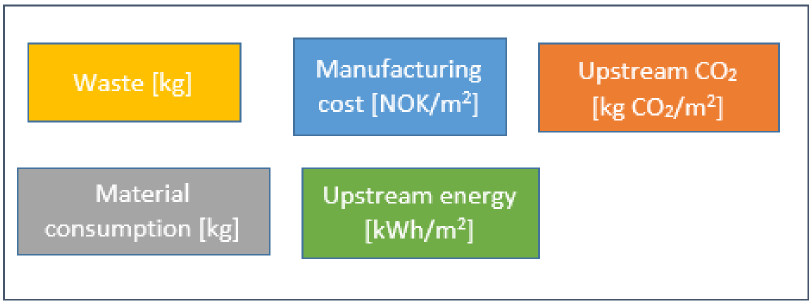


Figure 11: KPI values used in the material analysis of insulation materials

I have used two models, SIMIEN (Programbyggerne, 2014a) and TABULA (Loga & Diefenbach, 2013), when assessing the energy performance of the single-family example building in order to validate the results and get a broader insight into the differences between the two models.

Both of the models are energy balance models using the mass flow methodology (MFA). TABULA and SIMIEN may in addition be applied to different types of building systems and surroundings. It is in other words possible to adjust the input parameters for climate and building data, making it possible to assess the energy performance of buildings irrespective of country or location in the country, building type or time cohort of construction.

The upstream energy and CO_2 flows are calculated based on life cycle analysis (LCA), assessing a product's life cycle from cradle to construction site (stages A1 – A5 in Figure 12. The LCA methodology is described in ISO 14040 (European Commitee for Standardization, 2006a) and in Baumann and Tillman (2004). The different phases in the life cycle are based on the system description concerning life cycle phases in the standard NS-EN 15804 (Standard Norge, 2012).

The CO_2 emissions of the building during operation (stage B1 in Figure 12) is calculated based on CO_2 coefficients from Klimaløftet (2012). See Figure 12 below for a presentation of the different life cycle stages of a material.

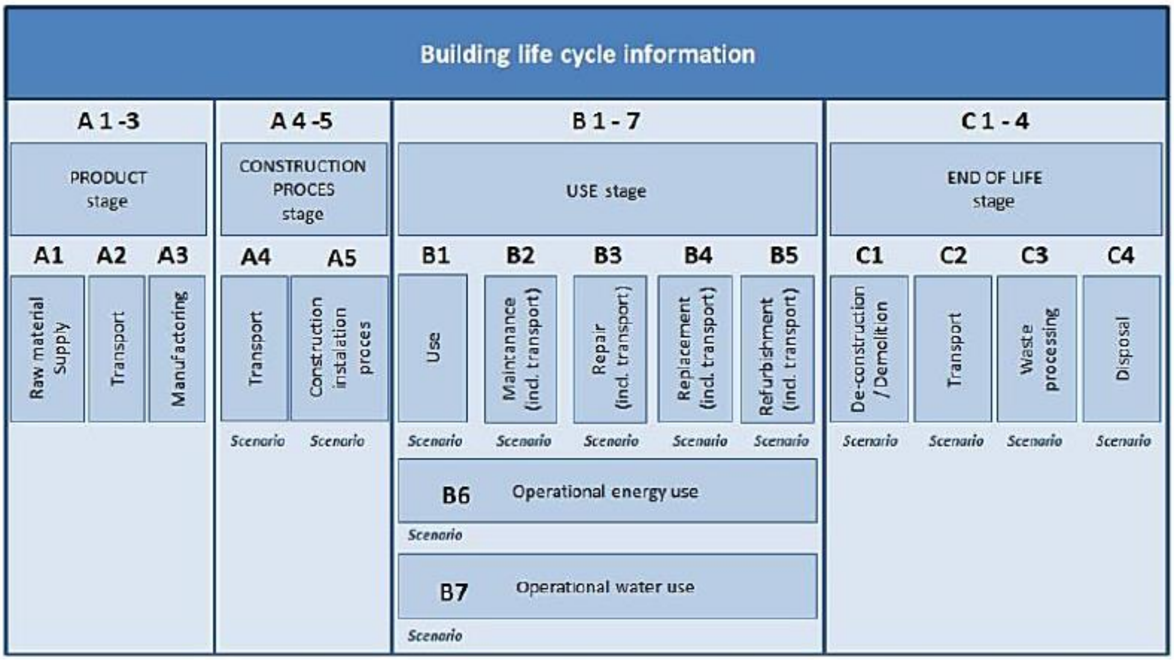


Figure 12: Life cycle stages of a material (SINTEF Fag, 2014a; Standard Norge, 2012)

3.1.2 Energy audit models

The core of an energy audit for a single house is to measure the dynamics influencing the energy balance in the dwelling The calculations used for finding the energy balance is based on the methodology of material flow analysis (MFA). In material flow systems, the flows are conserved; hence, the quantity of mass coming into the system is equal to the mass going out of the system. In order to apply the concepts of material management in a MFA, it is important to define proper system boundaries, a flow chart and stocks and flows (Brunner & Rechberger, 2004). However, in an energy audit model the flows from the building are not material flows, but energy flows going into or out of the system. The energy flows going out from the building are heat loss, caused by air infiltration, transmission heat loss through the building envelope, ventilation heat loss and heat loss through plugholes and ducted fans. Energy flows going in to the building constitute heat gain from heating systems, electrical equipment and lighting, irradiance and heat from people in the building (Standard Norge, 2014). In a dynamic system, it is also possible to store heat over a period in building constructions, furniture and other indoor surfaces, as well as in water containers and pipes.

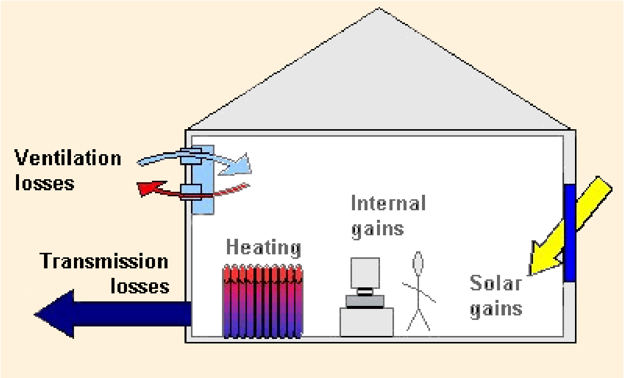


Figure 13: Elements of the heat balance in a building

TABULA

In contrast to using one system boundary including the building and corresponding heating systems, the TABULA energy audit model uses two energy balance systems: one for the building and one for the domestic hot water system. The TABULA project developed a standard reference calculation method for the energy needs and the delivered energy for space heating, in according to the seasonal and stationary method described in (International Organization for Standardization, 2008) on the basis of a one-zone model. This calculation method is adjusted to fit different building types with different energy performance levels in the building database. In addition, it is possible to assess the primary energy, CO_2 emissions and heating costs from an additional scheme in the model. The TABULA calculation method is generalized, and the user may apply the energy audit model to buildings located in any country. This is because the external boundary conditions, such as the air temperature and solar radiation, may be adjusted. For other factors, such as room temperature, air exchange rate and internal heat sources, standard values for the respective countries are applied. All equations used in the TABULA model may be found in (Loga & Diefenbach, 2013).

SIMIEN

Another common energy audit model used in the Norwegian industry is the software SIMIEN. It has been validated in coherence with the methodology in NS-EN 15265:2007 (International Organization for Standardization, 2008) and fulfills the requirements to accuracy with good scores (Programbyggerne, 2014b). SIMIEN performs energy simulations that are based on a simplified dynamic energy calculation method, calculating the energy flows of a building during one year. The algorithm is the same as the stationary and seasonal method presented in NS3031:2014 (2008), however, with dynamic external and internal climate input data that may change every 15 minutes. Input values in the model are adjusted to Norwegian conditions and are available in Standard Norge (2014). SIMIEN allows the user to have advanced input parameters of the energy systems of the building, climate data, building envelope, technical installations and internal load. During simulation, the energy performance of the one or multi-zone building is mapped, and the accumulated energy results are available in a report after the simulation. The data in the report includes, among others, the annual energy need and energy delivered for space heating and cooling for all energy carriers and a heat loss budget (Programbyggerne, 2014a).

Dynamic building stock model

I have used a dynamic segmented building stock model that is currently developed by Sandberg and Sartori (2015). The model presents changes over a time period in the dwelling stock, in terms of measuring the flows representing construction, demolition and rehabilitation activity in the building stock. When buildings are renovated, their energy balance will change and hence, so will the corresponding energy need for heating in the stock. The energy flow of the respective buildings is a built-in parameter that is up scaled when measuring energy characteristics for the entire stock or stock segments.

Population and number of persons per dwelling are drivers in the model, determining the dwelling stock demand for each year. Construction activity is equal to the sum of change in demand and what is needed to replace demolished dwellings, in accordance with mass balance principles (Sandberg et al., 2014b).

The dynamic model functions for renovation and demolition are based on discrete convolution and a probability function (Sandberg et al., 2014b). The model uses the probability functions $DEM_i(k)$ and $REN_i(k)$ in order to calculate the fraction of the inflow of dwellings of a particular stock segment that are demolished or renovated k years after construction and applies these functions for all previous years m in the simulation. The following equation is used in order to demonstrate the amount of renovated dwellings in year t in the simulation (Sandberg et al., 2014b):

$$D_{ren,i}\left(R_{C,i,t}\right) = \left(D_{in,i} * R_{c,i}\right)[t] = \sum_{m=t_0}^{t-1} D_{in,i}[m] \cdot R_{c,i}[t-m] \qquad 1$$

$D_{ren,i}$ = *Dwellings renovated in year t from stock segment i*
$R_{C,i,t}$ = *Value of the renovation cycle, hence, the average time period between refurbishments*
$D_{in,i}$ = *Inflow of dwellings in stock segment i*
$R_{C,i}$ = *Fraction of the inflow of dwellings from stock segment i that are renovated*
t = *Current year in simulation*
t_0 = *Year of construction for stock segment i*

R_c represents the average time period between refurbishments, also known as a renovation cycle. When long-term modeling a dwelling stock, each building will be renovated several times in accordance with the chosen renovation cycle.

The equation is expressed as a discrete convolution. In this context it may be described as the amount of dwellings from a stock segment going through renovation a particular year in the simulation, taking into account the amount of dwellings being constructed all previous years in the simulation .

The renovation function in the model is implemented in a way that prohibits dwellings from being renovated unless they are expected to be still standing long enough to justify the renovation. This is defined as at least the period of the renovation frequency. The renovation function is therefore dependent the demolition function and the parameter defining the intervals in the renovation function (Sandberg et al., 2014b).

3.2 Case description

The scope of this report is to study the energy and carbon emission reduction potential of Norwegian single-family houses built between 1971 and 1980 (SFH03) towards 2050 when adding different thicknesses of mineral wool and vacuum insulation to the outer walls. In order to achieve this objective, I will investigate the energy balance of one (1) typical single-family house from the 1970s, taken from a typology brochure for Norwegian houses from the EPISCOPE project (Brattebø & O'Born, 2014). Further, I will use the energy need for heating results from the energy audit for further calculations of the energy potential for the total dwelling stock segment when applying different types of insulation solutions. I will in addition do a material analysis of the different insulation solutions for one SFH03 building. Hence, analyze the material flows, additional investment costs related to manufacturing of new insulation, upstream energy and CO_2 flows and insulation waste at construction site (see Figure 11 for an overview of the KPI values).

The building may be in three different renovation levels, depending on the year of renovation of the SFH03 dwellings: Original, Historically refurbished, TEK 10 standard and passive house standard (see Table 9).

Before 1980 during the simulation, the SFH03 segment is assumed to remain at an original energy standard (Rn1), even if renovated. In the model by Sandberg and Sartori (2015), it is assumed that renovation of outer walls before 2010 was considered to be of a lower standard compared to today's technical building regulations (TEK 10) of new buildings. The buildings renovated before 2010 therefore goes under the category historically refurbished (Rn2). This is different from the definition of the time period of Rn2 in an ongoing study related to the EPISCOPE project, as their last year is 2020 for buildings renovated in Rn2. I have assumed that all buildings historically renovated to Rn2 use mineral wool insulation. This is because VIP materials are not a well-known material applied in house refurbishment in Norway.

The third level is split into three alternatives, depending on the ambitiousness of the renovation. All the alternatives will be studied in a scenario analysis. The insulation thickness requirements for wooden frame walls are in coherence with the technical building regulations (see Table 5 in chapter 2), when applying mineral wool insulation.

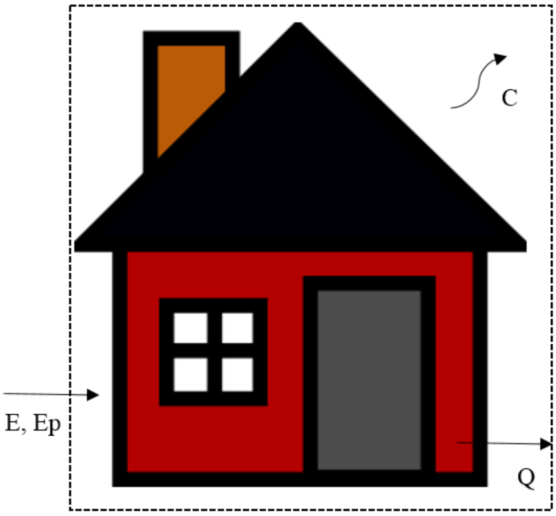
Table 9: Renovation levels and requirements when applying mineral wool insulation

Renovation level	Time period	Required insulation thickness [mm min. wool / mm VIP]
Rn1 Original	1971 - 1980	100 mm insulation
Rn2 Historically refurbished	1980 - 2009	150 mm insulation
Rn3, consisting of 3 alternatives: • Historically refurbished • Approaching TEK 10 standard • Approaching passive house standard	2010 - 2050	150 / 20 mm insulation 200 / 30 mm insulation 350 / 50 mm insulation

The input parameters used in the models are adjusted for Norwegian conditions. Hence, climate data from Oslo and other parameters such as indoor and building envelope data, are taken from Standard Norge (2014), Prognosesenteret & Entelligens (2011) and the TABULA typology brochure for Norwegian buildings (Brattebø & O'Born, 2014). Primary energy factors and CO_2 coefficients for the chosen energy carriers of the building are provided from Strømman (2014) and Ecoinvent. Data on material consumption for different insulation materials is provided from a report on insulation material analysis, conducted by SINTEF Fag (2014a). Other input parameters, such as costs and waste of the materials, are estimations made by workers and retailers in the building industry (Martinsen, 2015; Promat international, 2015).

3.2.1 System definition of one SFH03 building

The system boundaries for energy flows are defined to be around the building envelope of the example building, along the stapled lines of the square in Figure 14. In the energy audit, I have looked at energy flows and operational CO_2 emissions. In addition, there are the upstream energy and CO_2 flows from the manufacturing of new insulation materials that is being produced when refurbishing the building. A system drawing of the energy and CO_2 flows of the SFH03 example building is presented in Figure 14 below.



E = Delivered energy to the building [kWh/ m^2]
Q = Calculated energy need for heating [kWh/ m^2]
E_p = Primary energy to the building [kWh/ m^2]
C = Operational CO_2 emissions [kg CO_2/ m^2]

Figure 14: System drawing

3.2.2 System data

Building data

The example building used in this thesis work is a synthetic average building of a single-family house built between 1971 and 1980. The data of the building is taken from EPISCOPE's typology brochure for Norwegian houses (Brattebø & O'Born, 2014). Below there is a presentation of the building and its most important construction characteristics. Even though the building is synthetic, its building characteristics are similar to other example buildings of single-family houses built in the same time cohort (Prognosesenteret & Entelligens, 2011; SINTEF Fag, 2014b).

Table 10: Building characteristics for SFH (1971-1980).

Building component	U-value [W/m^{2}K]	Description	Area [m^2]
Outer walls	0.41	Timber frame walls with 100 mm mineral wool	186
Floor towards cold basement	0.24	48x148 mm joists. 150 mm mineral wool	87
Ceiling against attic	0.21	48x198 rafters. 200 mm mineral wool	87
Windows and doors	2.6	Double-pane windows, inflated normal glass	23

Figure 15: Single-family house built between 1971 – 1980 (Brattebø & O'Born, 2014)

Table 11: Building geometry and energy need for room heating [kWh/m^2]

Building geometry	Value
Heated floor area [m^2]	152
Wall area (external dimensions) [m^2]	186
Dimensions (width x length) [m]	10.8 x 7.0
Floor height [m]	2.4
Heated building volume [m^3]	380
Energy need for room heating [kWh/m^2]	152

Since SIMIEN and TABULA are two different models, there are parameters in each program that are unique for the respective model. Therefore, despite making the input data in SIMIEN approximately similar to the TABULA input data, it is not always possible to tell the right value. Concerning heat loss due to ventilation and infiltration, the calculation methods used in SIMIEN and TABULA are treated differently. Table 12 presents the most important infiltration and ventilation parameters that belong to the different models.

Table 12: Important infiltration parameters in TABULA and SIMIEN

Infiltration	Value	Model
$n_{air,infiltr}$ [1/h]	0.4	TABULA
$n_{air,use}$ [1/h]	0.4	TABULA
Surcharge on all U-values, ΔU_{tbr} [W/(m^2 envelope area K)]	0.05	TABULA
Normalized thermal bridge value, tb [W/m^{2}floor K]	0.13	SIMIEN
Air leakage rate, n_{50} [1/h]	5.7	SIMIEN
Natural ventilation, n_{inf} [m^3/hm^2]	1	SIMIEN

TABULA uses a thermal bridge factor that accounts for the heat loss caused by the thermal bridges in the building, ΔU_{tbr}. This is not the same as the normalized thermal bridge factor used in SIMIEN, which has a corresponding unit of W per m^2 building envelope area and not heated floor area. However, it is possible to calculate the corresponding value in SIMIEN by multiplying the surcharge factor with the envelope area and divide it by the heated floor area, see equation 17 in appendix 2.

Similarly, the natural ventilation factor in TABULA may be converted to the corresponding variable in SIMIEN, see equation 18 in appendix 2.

As for the leakage number, $n_{50,}$ this has been found by an internal converter between the leakage number and infiltration rate in the SIMIEN software.

In the TABULA methodology, there are different classifications for the heat losses due to ventilation, infiltration and surcharge on the U-values. The values in bold in Table 13 are the chosen values for the example building. As shown in, the surcharge factor on the U-values is classified as low and the infiltration parameters are classified as high.

Table 13: Infiltration variables in TABULA (Loga & Diefenbach, 2013)

Air leakage rate in TABULA	High	Medium	Low
ΔU_{tbr} [W/(m^2 envelope area K)]	0.15	0.1	**0.05**
$n_{inf,air}$ [1/h]	**0.4**	0.2	0.1
$n_{,use}$ [1/h]	**0.4**	0.08	0.04

The TABULA methodology uses two parameters for calculating the infiltration heat loss. Instead of using a unit that is a volume flow dependent on the heated floor area, like in SIMIEN [m^3/hm^2], TABULA uses a volume flow dependent unit related to a reference heated floor area and ventilation reference room height. The TABULA standard value for the standard room height is defined as 2.5 meters (Loga & Diefenbach, 2013).

In order to explore how robust the models are, I have done a sensitivity analysis in SIMIEN, which has given me a better understanding of how much a change in six chosen parameters may influence the building's energy performance. Due to limited time and the complexity of the TABULA program, I have not done a similar sensitivity analysis for both models. See the results chapter 4.3 for results of the sensitivity analyses and chapter 5.2.1 for a discussion about the robustness of the chosen parameters.

The insulation types are divided into mineral wool insulation and vacuum insulation. In this subchapter, the insulation material data used in the material analysis will be presented. The data is taken from an insulation material study by SINTEF Fag (2014a) and includes thermal characteristics, material densities, and upstream energy and CO_2 emissions.

When studying insulation materials, there are two material properties in particular that are of interest, the thermal conductivity, λ [W/mk], and the thermal resistance, R [m^2K/W]. See equation 8 for the correlation between λ and R. Both of these characteristics define the insulation ability of a material. The thermal resistance, R, is the inverse of the U-value [W/m^2K] (equation 9) and when evaluating the thermal quality of a construction part or a material, it is common to refer to the U-value.

The thermal conductivity, λ, is dependent on the temperature, density and moisture content of the material. Light materials are often more insulating than heavy materials due to the fact that light materials may contain air gaps filled with air, and still air is a good insulator. However, heat transfer may occur by radiation and convection as well. Water for instance transfers heat better than air and thus will make the material less insulating when it is wet rather than dry. This shows the importance of installing the insulation during rehabilitation and maintaining the insulation material dry throughout operation time (Bergman, 2007).

Table 14 below presents the four different insulation types, their thermal characteristics, densities and the required thickness to achieve a thermal resistance R = 1 [m^2K/W].

Table 14: Insulation material data

Insulation type	Type	Name of product	Thickness at R = 1 [mm]	Heat conductivity, λ_d [W/mK]	Density, ρ [kg/m^3]
Type 1	Mineral wool	Fiber glass	35	0.035	16.5
Type 2		Rockwool	37	0.037	29
Type 3	Vacuum insulation panel (VIP)	Dow Corning VIP	4.6	0.0046	185
Type 4		Microtherm SlimVac	7	0.007	185

As shown in Table 14, there is a significant difference between the two main insulation types' density and heat conductivity. For instance, mineral wool is of a significantly lighter material than vacuum insulation, having a density of less than 15 % of the vacuum insulation types. Mineral wool however, requires a thicker layer of insulation than vacuum insulation in order to achieve an R-value of 1 [m^{2}K/W].

Measurement of the upstream energy and CO_2 emission flows of the different insulation materials requires reliable data on the energy use and CO_2 emissions from cradle to construction site (A1 – A5 in Figure 12). The data is taken from a study on different insulation materials by SINTEF Fag (2014a).

Table 15 presents the amount of energy or CO_2 used when producing 1 m^2 of insulation material that has an R-value equal to 1 [m^{2}K/W].

Table 15: Upstream energy and CO_2 emissions from different insulation materials

Type	Name of product	Emission intensity A1 – A5 [Kg CO_2]	Energy intensity A1 – A5 [kWh]
Mineral wool	Fiber glass	0.745	5.27218
	Rockwool	1.282	3.88056
Vacuum insulation panel (VIP)	Dow Corning VIP	9.491	45.28553
	Microtherm Slim Vac	8.151	54.89252

As shown, mineral wool materials use far less energy and pollute less than vacuum insulation materials in the process from cradle to construction site.

In collaboration with the supervisors, it was decided that I should study two insulation types in this master's thesis. These types are defined as an average of the mineral wool types and an average of the vacuum insulation types. Hence, the heat conductivity and density properties will be a hybrid between the two subtypes. Similarly, the upstream energy and emission parameters will be an average of the two main insulation types. See Table 16 and Table 17 for a presentation of the main insulation types and their respective thermal characteristics and corresponding U-values for the different renovation solutions and upstream emission and energy flows.

Table 16: Main insulation types and their respective thermal characteristics

Type	Heat conductivity, λ_d [W/mK]	Density, ρ [kg/m^3]	U-value historically refurbished	U-value TEK 10	U-value passive house
Mineral wool	0.0360	23	0.29	0.18	0.10
Vacuum insulation	0.0058	185	-	0.19	0.12

Table 17: Energy and emission intensities for the main insulation types

Type	Emission intensity A1 – A5 [Kg CO_2]	Energy intensity A1 – A5 [kWh]
Mineral wool	1.02	4.58
Vacuum insulation	8.82	50.09

When adding new insulation, there is an option of keeping some or all of the original insulation or removing all original insulation and replacing the old in addition to adding new. Despite knowing a typical U-value of the original outer wall of the example building, the insulation types used were many and of varied quality. Workers from the construction industry state that there are huge variations depending on the house’s condition when they evaluate if some of the original insulation should be kept in addition to adding new when refurbishing (Martinsen, 2015; Solid Prosjekt AS, 2015). For practical reasons, I have chosen to assume that all original insulation is removed when renovating the façade of the building.

Dahlstrøm (2012) assumes that there is no waste from mineral wool on the construction site when adding new insulation. This is because the size of the insulation mats is already determined when ordering the materials needed (Dahlstrøm, 2012). However, according to workers in the contracting and real estate development firm Solid Prosjekt AS, about 4-5 % of insulation materials goes to waste on the construction site. Unopened packages and whole insulation mats or plates are not accounted for in this statement, as these will be used in new projects (Martinsen, 2015; Solid Prosjekt AS, 2015). Few workers in the Norwegian construction industry have experience with vacuum insulation. Hence, there are no estimates on the share of waste of VIP material during refurbishment of the outer walls. It is however reasonable to assume that due to the vacuum insulation consisting of plates, there is little waste when installing the panels. I conclude with assuming 5 % waste of mineral wool and 0 % waste of vacuum insulation at the construction site.

Energy mix, primary energy factors, energy cost and interest rate

The energy mix of the building should reflect the average energy mix among single-family houses built in the defined time cohort of 1971 and 1980 (SFH03). In the TABULA project the SFH03 average synthetic building has an energy mix consisting of 80 % electricity and 20 % bio wood and is found to be representative for this dwelling stock segment (Brattebø & O'Born, 2014). I will therefore choose the same energy mix. See Table 18 for a presentation of the power efficiency factors, η_j, for the j number of different energy

Table 18: Power efficiency factors, , for the different energy carriers in the heating system

Energy carrier	Power efficiency for room heating, η_j	Source
Fireplace	0.64	TABULA
Electricity	1	TABULA

Table 19: Primary energy factors and CO_2 production coefficients

Energy carrier	Non-renewable PEF	Total PEF	CO_2 production coeff. [kg/kWh]	Source
Bio wood / Fir log	0.09	1.09	0.261	(Klimaløftet, 2012; Strømman, 2014)
Electricity (Norway)	0.27	1.28	0.05	(Ecoinvent; Klimaløftet, 2012)

The primary energy is calculated by multiplying the delivered energy with the respective primary energy factor of an energy carrier. Primary energy is the energy in the state found in nature without being transformed or converted. A PEF has two conventions: a total and a resource primary energy factor. The total takes into account all of the transportation, extraction, processing and storage losses before the energy gets to the point of use. In addition, it may include energy required to build the transformation and transportation units and the energy demand of disposing wastes. Waste may for example be ashes from a bio boiler. The resource primary energy factor is identical, but excludes the renewable energy consume of the primary energy. This factor may therefore be less than unity for non-renewable energy sources.

There is a big difference between the PEF of electricity in Norway and the PEF for Scandinavia, linked to the Norwegian grid. This will results in two very different primary energy consumptions, depending on the chosen PEF for electricity, as the PEF for Norway does not account for export and import of power to the grid. The PEFs are published by Ecoinvent and these are the factors used by TABULA for Norwegian dwellings (Ecoinvent; Loga & Diefenbach, 2013).

The CO_2 coefficients are taken from the webpage “Klimakalkulatoren”, a webpage provided by the government page which gives an overview of emissions in Norwegian households (Klimaløftet, 2012). The calculated coefficients are based on the average Norwegian electricity mix from the period 2007 to 2011. The reason for utilizing the average values from this period is in order to smooth variations in precipitation and outdoor temperature. Similarly, the numbers for electricity production and trading are an average from the same period.

As for the energy price used in the economic calculations, I have chosen to use an average value for the electricity price the last three years from SSB (2015) for calculating the payback time for renovating the outer walls. The energy price includes taxes and user dependent grid rental and is defined to be 0.8367 [NOK/kWh].

I have chosen a baseline interest rate, r, of 5 % in the cost calculations of this thesis. This is in between the national base rate provided by Norges bank (Norges Bank, 2015) and a typical interest rate in an invest analysis by a private company that aims for high profits.

Investment costs

I have chosen to do a simplified economic analysis, showing the investment cost of manufacturing insulation materials relative to the energy saved over a time period of 40 years. 40 years is the assumed average time interval between façade refurbishments. See equation 16.

Unfortunately, it has been challenging to get in contact with the producers of vacuum insulation panels. For this reason, I could not get a price offer on the Dow Corning VIP insulation. The producers of Microtherm insulation have, however, offered prices, and I will therefore proceed the cost calculations of VIPs with the prices for Microtherm (Promat international, 2015). Promat international manufactures their products in Denmark and offers products in a Danish currency. The NOK/DKK currency used in the cost calculations is 1.12 [NOK/DKK] and taken from the finance newspaper, *Dagens Næringsliv’s,* currency calculator (DN, 2015). Transportation costs from Denmark to Norway has not been accounted for in the cost calculations.

The producers of Rockwool insulation gave me the purchase price of their products, which corresponds to the cost of producing their products (Rockwool, 2015). The producers of Glava insulation referred me to retailer shops for prices of their products instead of giving the manufacturing price from the factory. The contact person in Rockwool, Dag Ove Leraand, assumes that the pricing level between Glava and Rockwool insulation products are about the same. Therefore, I assume that the price for mineral wool insulation is the same regardless of the insulation brand utilized. The final prices used in this master's thesis are the assumed prices contracting firms receive when purchasing insulation products. According to Leraand in Rockwool, the average discount price is 9 %. This discount estimate is used in further cost calculations.

Between the two mineral wool types, there are minimal differences thermal characteristics and therefore the average energy savings for mineral wool are used in the cost calculations. See Table 20 for a presentation of the investment costs for the chosen insulation types. All investment costs are rounded off to the nearest integer.

Table 20: Investment costs per heated floor area for mineral wool and VIP insulation

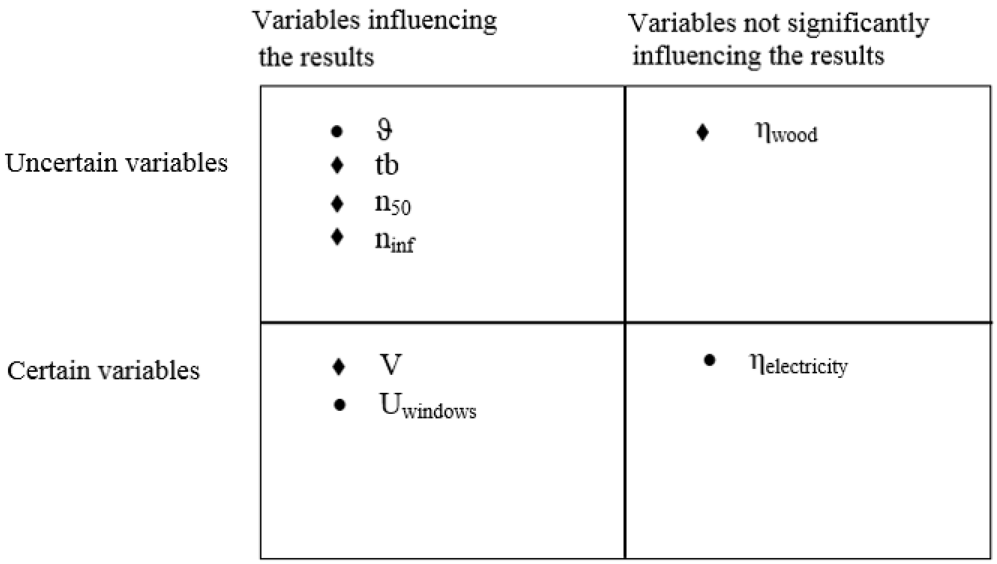
	Insulation type	Historical refurbished state	~TEK 10	~Passive house standard
Investment cost [NOK/m^2 floor]	Min.wool	81	93	195
	VIP	-	264	467

Table 21: Investment cost per SFH03 dwelling for mineral wool and VIP insulation

	Insulation type	Historical refurbished state	~TEK 10	~Passive house standard
Investment cost [NOK]	Min.wool	12 312	14 113	29 647
	VIP	-	40 186	70 952

3.3.3 Variable uncertainty and sensitivity analysis

When calculating the heating demand of a building, many variables both have an uncertainty concerning value and may influence the result for heating demand. In order to validate the energy results, it is important to identify which parameters to investigate further in a sensitivity analysis. One approach may be to utilize an uncertainty matrix. See Figure 16.



	Variables influencing the results	Variables not significantly influencing the results
Uncertain variables	● ϑ ♦ tb ♦ n_{50} ♦ n_{inf}	♦ η_{wood}
Certain variables	♦ V ● $U_{windows}$	● $\eta_{electricity}$

Figure 16: Uncertainty matrix

The uncertainty matrix is a quadrant divided into four cells with rows representing the uncertainty of the variables and columns representing the sensitivity of the energy results. The corresponding symbols to the variables indicate if the variables are case specific or general. Hence, the circle implies that the variable is general for the chosen stock segment and is found in literature and statistics. The diamond symbol implies that the variable is specific for the current building. For another case, the value would be different. The variables in Figure 16 are only examples that may fit the respective cell descriptions.

Variables that fit the cell description in the fourth cell in the lower right corner are variables with a certain value, which do not influence the energy result much. These variables are irrelevant for a sensitivity analysis. Likewise, for variables in the upper right corners. Perhaps the variable’s value is uncertain, but it does not influence the energy result, which we are interested in examining, hence, these variables may also be neglected in a sensitivity analysis. The variables in the remaining cells are variables that do influence the energy results and are worth investigating further in order to validate the energy results.

The uncertainty matrix lays the foundation for the chosen parameters in the sensitivity analysis in this master’s thesis. See Table 22 for the variables utilized in the sensitivity analysis and their corresponding baseline value and description.

Table 22: Variables in the sensitivity analysis

Parameter	Baseline value	Definition
ϑ [°C]	20	Average indoor temperature
tb [W/m^{2}K]	0.13	Normalized thermal bridging factor
n_{50} [1/h]	5.7	The air leakage rate under a building reference pressure of 50 Pa
n_{inf} [m^3/hm^2]	1	Exhaust air per hour per square meter floor area
V	380	Conditioned building volume
α_{frame}	0.3	Frame/window ratio: Area of the window given to the window frame

3.3.4 Stock and flows for the segmented stock model

According to Statistics Norway in 2010, the number of occupied single-family houses built in this time cohort was 206,011, corresponding to 29.2 million m^2 of user space (Prognosesenteret & Entelligens, 2011). This is equal to 24.8 million m^2 of heated floor area by assuming that 85 % of a user space area is conditioned. I will study the development of this segment of the Norwegian dwelling stock towards the year 2050 when different insulation solutions are conducted concerning floor area, energy need for heating, CO_2 emissions and upstream CO_2 flows. Table 23 presents the different scenarios evaluated in the scenario analysis for the outer wall of the building and the specific annual energy need. The values for energy need for heating are the only input values needed for this scenario analysis in the building stock model utilized in this master's thesis (Sandberg et al., 2014b).

Table 23: Scenario description and their corresponding U-values [W/m^{2}K]

Scenarios	Scenario description	U-value outer wall [W/m^{2}K]
Scenario 1	Baseline scenario. Maintaining level of historical refurbishment	0.29
Scenario 2	Approaching TEK 10 standard, min. wool	0.18
Scenario 3	Approaching TEK 10 standard, VIP	0.19
Scenario 4	Approaching passive house standard, min. wool	0.10
Scenario 5	Approaching passive house standard, VIP	0.12

3.3 Assumptions

When performing the case study for SFH03 as one example building and as a segment in the Norwegian dwelling stock, I have made several assumptions. The main assumptions are summed up below.

- The synthetic building is equal for all buildings in the building stock segment. I am only looking at changes in energy use for different insulation solutions.
- The energy mix for heating purposes of single-family houses consists of 90 % electricity and 10 % bio wood.
- All insulation materials have a lifetime of 40 years, which is the expected timespan of changing the facade. Hence, a renovation frequency of 40 years is assumed when changing the façade and adding new wall insulation to a dwelling.
- Renovation level 3, Rn3, includes all SFH03 buildings renovated from the year 2010.
- All original wall insulation is removed and substituted by supplementary insulation.
- I have assumed an average of mineral wool and vacuum insulation characteristics when doing the scenario analysis. A combination of the mineral wool types reflects the insulation choice in Norwegian households.
- I have assumed a baseline scenario where the past trend is maintained from 2010 to 2050. The past renovation trend has been renovating to a historical refurbishment level, corresponding to Rn2.
- When evaluating the investment costs, it is assumed that the household that is renovating is changing the façade regardless of adding extra insulation to the outer walls.
- I have conducted an investment cost analysis which excludes the installation costs of changing the façade and adding extra insulation and only looked at the material costs relative to the energy savings.
- The Dow Corning VIP costs are approximately the same as Microtherm insulation.
- The Danish currency is defined as 1.12 DKK/NOK (15.05.15).
- The price of mineral wool insulation is assumed to be the purchase price from Rockwool.
- Contract firms receives a 9 % discount on insulation products.
- 5 % of mineral wool and 0 % of vacuum insulation gets wasted at the construction site.
- Transportation and installation costs of insulation is not accounted for in the investment calculations.

4. Results

In the following chapter, results from the energy audit and material analysis for the SFH03 house will be presented, followed by an investment analysis for the different façade refurbishment solutions. Further, results related to the long-term dwelling stock modeling of the SFH03 segment in the Norwegian dwelling stock will be presented. This includes stock development [m^2] and energy and CO_2 results from the scenario analysis. Different renovation cycles of 30, 40 and 50 years are applied in the modeling. Lastly, a sensitivity analysis from the SIMIEN software will be presented.

4.1 The energy audit and material analysis of one SFH03 building

Table 24 presents results from the material and energy analysis of the chosen SFH03 house when using mineral wool and vacuum insulation approaching TEK 10 and passive house requirements. The waste parameter represents the waste from mineral wool production and the original mineral wool insulation from the building. The upstream flows represent the energy and carbon emissions required to manufacture and transport the insulation materials to the construction-site. Table 26 presents the same results from the material analysis scaled up to building level.

The material analysis shows that the mineral wool material stands out positively, with a low material consumption and low upstream CO_2 emissions. Vacuum insulation emits high levels of CO_2 and has a high upstream energy. The material consumption [kg] between the two insulation types is quite similar.

Table 24: Material flows and upstream energy and CO_2 flows for one (1) SFH03 building per heated floor area m^2, when applying different insulation solutions for the outer walls

Insulation type/thickness	Material need [kg/m^2]	Waste (original+ new insulation) [kg/m^2]	Upstream energy intensity [kWh/m^2]	Upstream CO_2 emissions [kg CO_2 /m^2]
Historically refurbished Min. wool (0.15 m)	4.4	3.0	20.3	4.5
TEK 10 Min. wool (0.2 m)	5.9	3.1	32.3	7.2
TEK 10 VIP (0.03 m)	6.8	2.8	317.0	55.8
Passive house Min. wool (0.35 m)	10.2	3.3	57.1	12.7
Passive house VIP (0.05 m)	11.3	2.8	528.4	93.0

Table 25 and Table 27 show the energy audit for the example building in the different renovation states when applying the different insulation solutions. The energy audit of one (1) SFH03 building presents four different parameters: energy need for heating, delivered energy, primary energy and operational carbon emissions (stage B1 in Figure 12). As shown, all of the flows decrease in value when extra insulation is added to the outer walls. In addition, they decrease with the same ratio. This is because the delivered energy, primary energy and carbon emissions are scalars of the energy need for heating, scaled up by efficiency factors, primary energy factors and CO_2 coefficient factors.

Table 25: Energy and CO_2 flows for one (1) SFH03 building per heated floor area m^2, when applying different insulation solutions for the outer walls

Insulation type/thickness	Energy need [kWh/m^2]	Delivered energy [kWh/m^2]	Primary energy [kWh/m^2]	CO_2 emissions [kg CO_2 eq./m^2]
Original (0.1 m)	152	163	202	15
Historically refurbished Min. wool (0.15 m)	138	148	184	14
TEK 10 Min. wool (0.2 m)	128	137	170	13
TEK 10 VIP (0.03 m)	129	138	172	13
Passive house Min. wool (0.35 m)	122	131	162	12
Passive house VIP (0.05 m)	123	132	164	12

Table 26: Material flows and upstream energy and CO_2 flows for one (1) SFH03 building when applying different insulation solutions for the outer walls

Insulation type/thickness	Material need [kg]	Waste [kg]	Upstream energy [kWh]	Upstream CO_2 emissions [kg CO_2 eq.]
Historically refurbished Min. wool (0.15 m)	666	456	3 081	684
TEK 10 Min. wool (0.2 m)	889	468	4 914	1 091
TEK 10 VIP (0.03 m)	1 032	423	48 190	8 485
Passive house Min. wool (0.35 m)	1 555	501	8 687	1 929
Passive house VIP (0.05 m)	1 721	423	80 317	14 142

Table 27: Energy and CO$_2$ flows for one (1) SFH03 building when applying different insulation solutions for the outer walls

Insulation type/thickness	Energy need [kWh]	Delivered energy [kWh]	Primary energy [kWh]	CO$_2$ emissions [kg CO$_2$ eq.]
Original (0.1 m)	23 104	24 767	30 761	2 284
Historically refurbished Min. wool (0.15 m)	20 976	22 486	27 928	2 073
TEK 10 Min. wool (0.2 m)	19 456	20 857	25 904	1 923
TEK 10 VIP (0.03 m)	19 608	21 020	26 107	1 938
Passive house Min. wool (0.35 m)	18 544	19 879	24 690	1 833
Passive house VIP (0.05 m)	18 696	20 042	24 892	1 848

Figure 17 presents the heat loss budget of the example building chosen in this master's thesis and the distribution of the thermal loss in the different building components in SIMIEN and TABULA. As shown, the heat loss from ventilation, walls and windows are the biggest heat loss sources.

The ventilation heat loss counts for almost 1/3 of the building's total transmission loss in both models. However, TABULA has an 8 % bigger heat loss due to ventilation than SIMIEN. At the same time, TABULA has a heat loss from the floor that is only half as big as in SIMIEN.

Figure 17: heat loss budget for the SFH03 building in TABULA and SIMIEN

In addition to slightly different heat loss budgets, Table 28 shows a comparison of the energy need for heating in original state in SIMIEN and TABULA. The unit utilized is energy per heated floor area. As shown, the two models yield almost the same result for energy need, with a discrepancy of 3 %.

Table 28: Comparison of energy need for heating in original state (Rn1) in SIMIEN and TABULA

Energy need for heating [kWh/m^2]		
SIMIEN	TABULA	$\frac{TABULA-SIMIEN}{SIMIEN}$ [%]
156	152	- 3.0 %

Figure 18 and Figure 19 are graphical illustrations of the total energy need for heating for a SFH03 building in its original and historically refurbished state, upgraded to TEK 10 and passive house standard. The parentheses used on the x-axis represent the insulation thickness, where the smallest thicknesses are used when applying vacuum insulation and the bigger ones are for mineral wool insulation. In order to compare different insulation materials with each other, I have chosen the same insulation thickness size for vacuum insulation and mineral wool insulation and made my calculations based on the average of these values. A consequence is that the corresponding U-value of the dwelling's outer walls merely approaches the TEK 10 and passive house requirements rather than fulfilling the exact requirements. Hence, the U-values for the outer walls when using vacuum insulation are slightly higher than the U-value requirements for the TEK 10 and passive house standard.

The upgrade to TEK 10 and passive house standard will decrease the energy need of the dwelling substantially, from 152 kWh/m^2 in heating demand to respectively 138, 128 and 122 kWh/m^2 for mineral wool, depending on the insulation solution. This corresponds to 9, 16 and 20 % in energy savings. The vacuum insulation solutions yield on average a slightly higher value for the energy need for heating: respectively 129 and 123 kWh/m^2 when approaching TEK 10 and passive house standard.

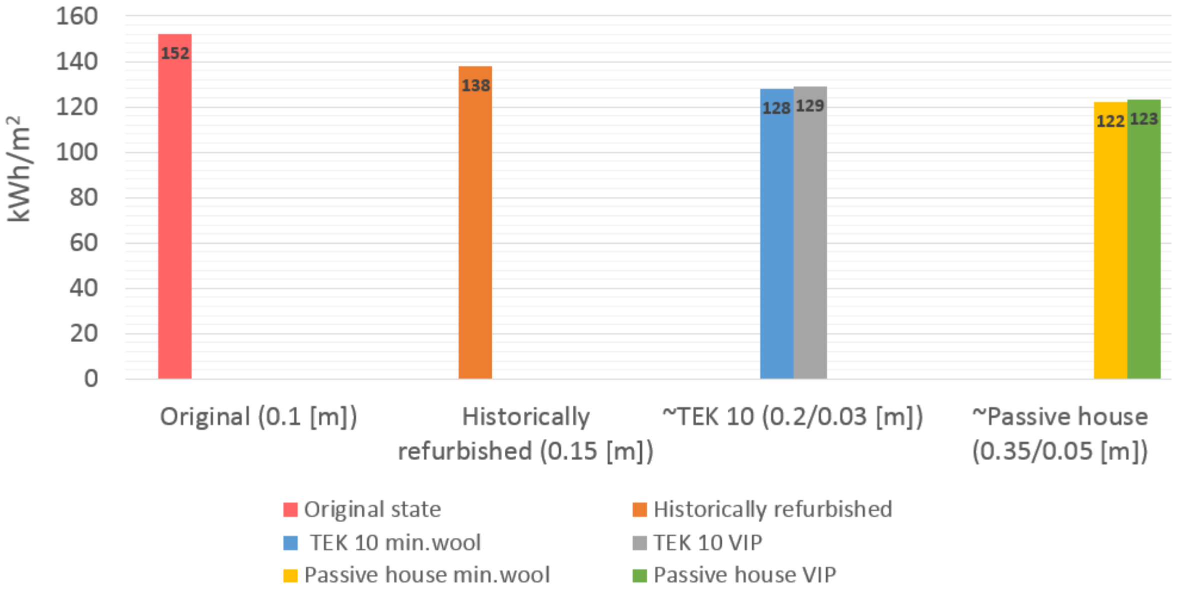


Figure 18: Annual energy need for heating with the different insulation solutions [kWh/m2]

Figure 19 presents the same information as Figure 18, but the unit is corresponding to annual energy need for heating per SFH03 building and not per m^2 heated floor area. See Table 27 for the actual values.

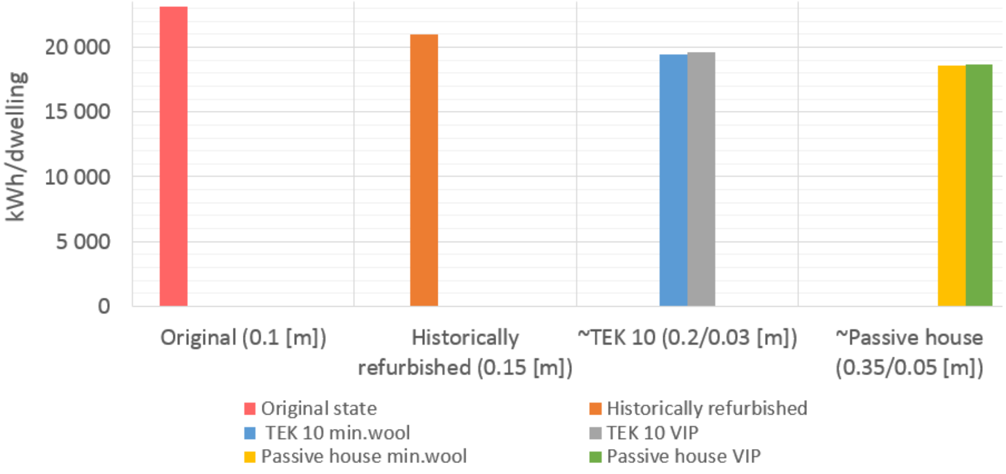


Figure 19: Annual energy need for heating with different insulation solutions [kWh/dwelling**]**

4.2 Investment costs

Table 29resents the investment costs for different insulation solutions when renovating the façade, using an energy price of0.8367 [NOK/kWh]. The costs used in the calculations are explained in chapter 3.2.2. Only mineral wool insulation is applied for the historical refurbishment. The annual energy savings is equal to the difference in annual heating demand when introducing the more advanced insulation solutions to the original state.

Table 29: NPV values for the different insulation solutions. The interest rate, r, is set to 5, 6 and 7 %.

Insulation solution	Annual energy savings [kWh/m^2]	NPV [NOK/m^2 floor]		
		r = 5 %	r = 6 %	r = 7 %
S1, BL, min. wool historically refurbished	14	+ 120	+ 95	+ 75
S2, min. wool ~TEK 10	24	+ 252	+ 209	+ 175
S3, VIP ~TEK 10	23	+ 66	+ 26	- 7
S4, min. wool ~passive house	30	+ 236	+ 183	+ 140
S5, VIP ~passive house	29	- 51	- 102	- 144

As shown, the net present value (NPV) for all insulation solutions using mineral wool are positive. Conducting mineral wool insulation to TEK 10 standard yields the highest NPV value of all the alternatives, followed by passive house standard and historical refurbishment.

The VIP materials are more expensive and hence give a lower NPV. However, the VIP TEK10 insulation solution results in a positive NPV for an interest rate, r, equal to or lower than 6 %. VIP approaching passive house standard is the only insulation solution with a negative NPV in all the calculations.

Figure 20 shows the resulting NPV values for the different insulation solutions when changing the energy price from 0.8367 NOK/kWh (BL). As shown, all mineral wool insulation solutions are economically viable when changing the energy price up to ± 100 %. The insulation solution for TEK 10 mineral wool is the most economically viable solution.

VIP insulation when upgrading to TEK 10 gives a positive NPV for all energy price alternatives that have decreased with less than 30 % from the baseline price. VIP insulation corresponding to passive house standard is economically viable for an energy price increased by 15 % or more. For all other price alternatives, VIP passive house standard gives a negative NPV value.

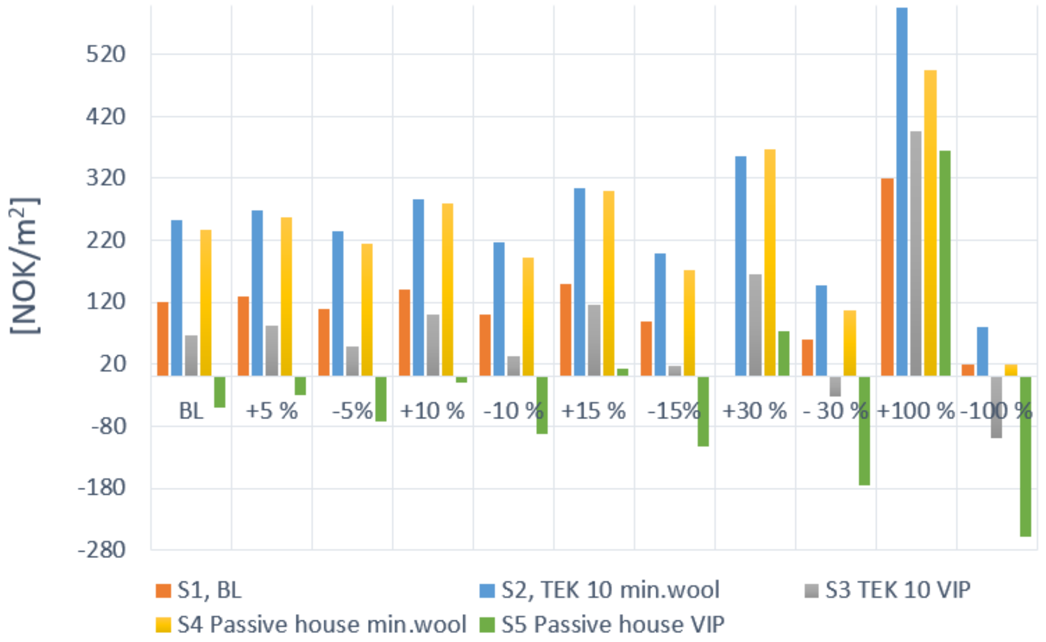


Figure 20: Net present value (NPV) when changing the energy price. The interest rate, r, is set to 5 %.

4.3 Long-term modeling of the SFH03 housing segment towards 2050

4.3.1 Dwelling stock development and renovation activity [m^2]

Figure 21 shows the baseline dwelling stock development of SFH03 from the year 2000 to 2050 in heated floor area [m^2]. The output unit in the model is the number of SFH03 dwellings for each year. Hence, in order to convert the number of buildings to heated floor area, the average heated floor area of 152 m^2 is defined as an input parameter in the model.

All three renovation states, Rn1, Rn2 and Rn3, are included in the results. Rn1 represents all dwellings that are in their original state, whereas Rn2 represents renovated dwellings between 2000 and 2010 in a historically refurbished state and Rn3 renovated dwellings after 2010 to 2050.

As shown, the total stock segment decreases from its initial value in 2000 due to demolition during the time period of the simulation. In 2050, the total heated floor area has been reduced with 27 % compared to the area in 2000. In addition, the SFH03 dwellings in renovation state Rn1 decrease significantly from the year 2000 to 2050 in the simulation: starting at 20.3 million m^2 and decreasing to 1.1 million m^2. This is equal to a 95 % decrease in heated floor area. Hence, according to the results from the housing stock model, 95 % of the heated floor area in original state (Rn1) in the year 2000 will have been renovated in 2050.

The first 10 years of the simulation, a large part of the dwellings in Rn1 is upgraded to a historically refurbished state, Rn2, and no demolition is conducted until 2010. The amount of renovated dwellings in renovation state Rn2 stays more or less constant throughout the simulation and hence, only a small share of dwellings in Rn2 are demolished.

From 2010, dwellings are upgraded to Rn3 when going through refurbishment. The share of renovated dwellings increases throughout the simulation and in 2050, dwellings in Rn3 – renovated from 2010 – 2050 - represent 11.5 million m^2 and the total amount of renovated dwellings from Rn2 and Rn3 exceeds 14.6 million m^2. This is equal to 93 % of the total SFH03 housing stock segment.

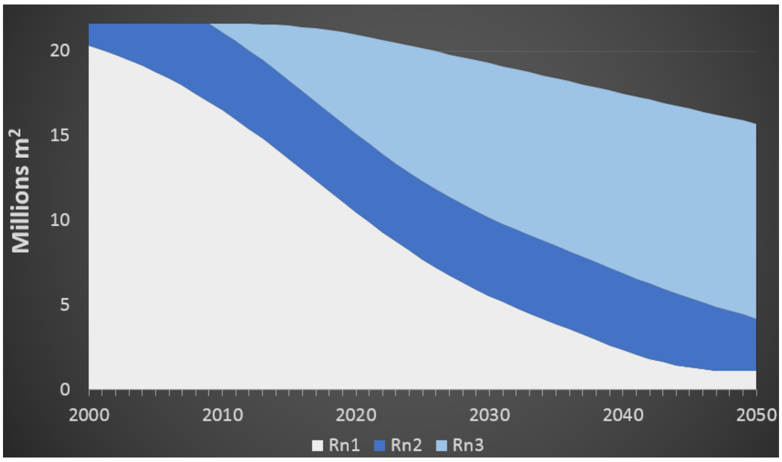


Figure 21: Baseline scenario of the dwelling stock composition of SFH03 in renovation state Rn1, Rn2 and Rn3 [m2], assuming a renovation cycle of 40 years.

Figure 22 and Figure 23 show the stock composition of SFH03 in its three respective renovation states when assuming average time between renovation to change to 50 and 30 years. Figure 23 shows that the share of dwellings representing SFH03 buildings in Rn2 in the 50-year renovation cycle is smaller compared to the share of dwellings in Rn2 following the 30-year renovation cycle in Figure 22. The share of Rn2 in the 50-year renovation cycle in 2010 constitutes 7 % of the stock segment. In comparison, the dwellings in Rn2 in a 40-year renovation cycle represent 21 %. Vice versa, when renovating more often, like for buildings following the 30-year renovation cycle, the share of SFH03 buildings upgraded to Rn2 in the period 2000 – 2010 is significantly higher, representing 59 % of the total stock segment. This is almost three times more than for dwellings following the 40-year renovation cycle and eight times more than for dwellings following the 50-year renovation cycle. |

A less frequent renovation cycle also results in a lower total amount of renovated dwellings in 2050. When renovating the façade every 50 years, it results in a total renovated floor area of 11.5 million m^2, hence 20 % lower than when renovating every 40 years. As for the graph representing the 30-year renovation cycle, the total amount of renovated dwellings is equal to the graph representing the baseline renovation cycle of 40 years.

It may seem like the dwellings in Rn2 increase somewhat in value between the year 2030 and 2035 in Figure 23. However, this is not the case since Rn2 can only decrease in value after the year 2010, and the values for Rn2 are constantly decreasing throughout the simulation in the building model. The reason why the Rn2 segment seem to increase is that the Rn1 segment of the SFH03 buildings has stopped decreasing and remains constant from 2030.

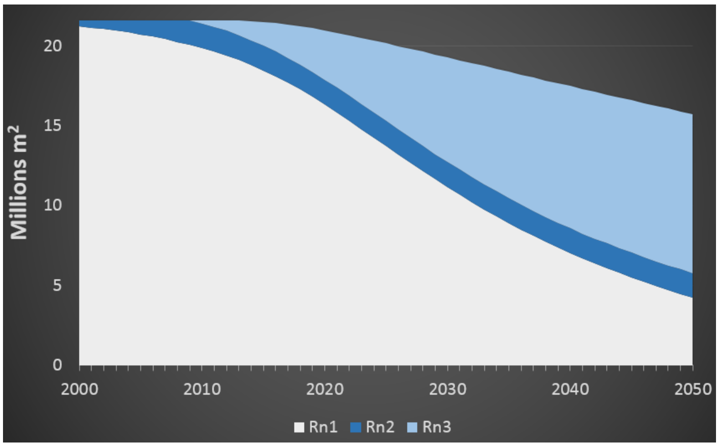


Figure 22: Dwelling stock composition of SFH03 in renovation state Rn1, Rn2 and Rn3, assuming a renovation cycle of 50 years.

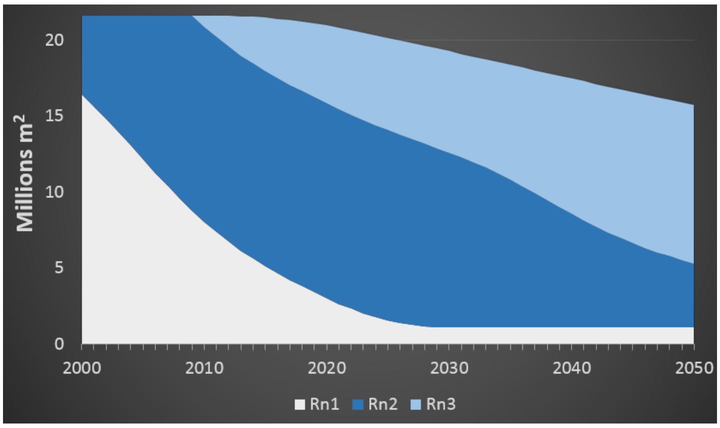


Figure 23: Dwelling stock composition of SFH03 in renovation state Rn1, Rn2 and Rn3, assuming a renovation cycle of 30 years.

Figure 24 presents the total amount of the heated floor area [m^2] of the dwelling stock segment SFH03 in renovation state Rn3 when conducting renovation cycles of respectively 30, 40 and

50 years. Hence, the graph illustrates the quantity of renovated dwellings from the year 2010 in the simulation. As shown, a frequency of 40 years between renovations will result in the largest amount of renovated dwellings in this stock segment, representing 11.5 million m^2 in 2050. This is 14 and 9 % less than using renovation cycles of respectively 50 and 30 years.

The function with a 30-year renovation frequency also has the steepest slope in the beginning of the simulation. Hence, a larger amount of SFH03 buildings is renovated between 2010 and 2015 for the graph representing the 30-year cycle than for the two other functions. However, the slope decreases the next couple of decades, resulting in fewer refurbishments among SFH03 buildings compared to dwellings following a 40-year renovation cycle. The graph representing the 50-year renovation cycle is below the other graphs in refurbishment with the exception of the time period from 2030 to 2040. In that period, more renovations are conducted for dwellings following a 50-year renovation cycle than for those refurbished every 30 years.

One clear observation is that the three line graphs have their highest renovation activity, also known as the slope of the line graph, in different times in the simulation. The 30-year cycle has its highest renovation activity around year 2010, the 40-year renovation cycle around year 2020 and the 50-year renovation cycle around year 2030.

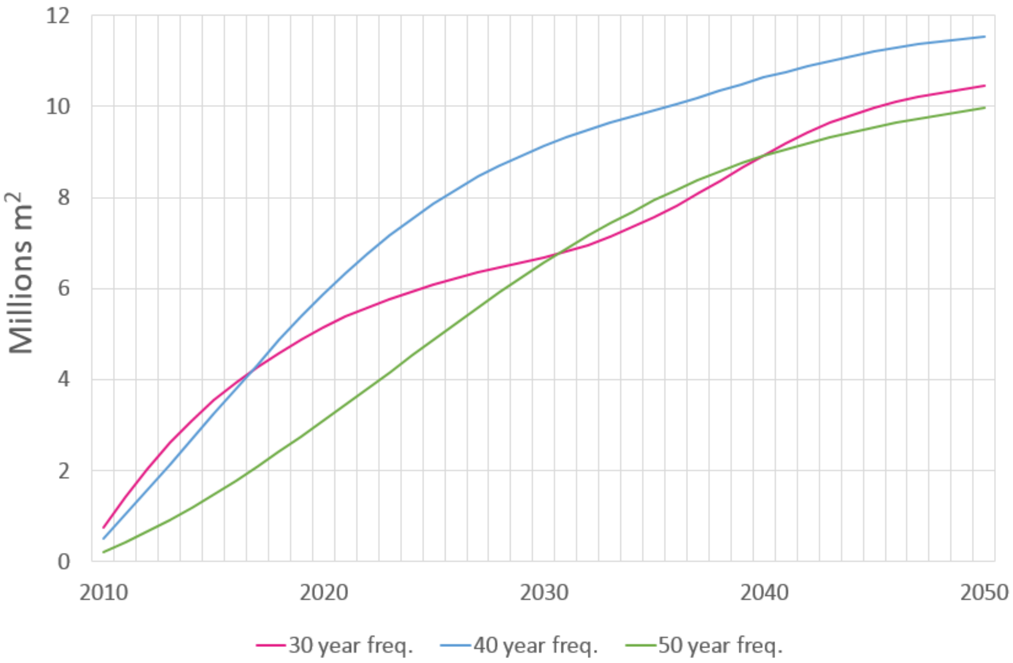


Figure 24: Renovation cycle analysis of the SFH03 dwelling stock segment in renovation state Rn3

4.3.2 Scenarios

Table 30 presents the different scenarios in the scenario analysis in this master's thesis. The scenarios are insulation solutions applied to the SFH03 segment in renovation state Rn3 from 2010 to 2050.

Table 30: Presentation of the scenarios applied in the scenario analysis, defining the renovation state Rn3

	Scenario description	Heating demand [kWh/m^2]
Scenario 1	Baseline scenario. Maintaining level of historical refurbishment	138
Scenario 2	Approaching TEK 10 standard, min. wool	128
Scenario 3	Approaching TEK 10 standard, VIP	129
Scenario 4	Approaching passive house standard, min. wool	122
Scenario 5	Approaching Passive house standard, VIP	123

Figure 25 - 27 show the energy need for heating of the SFH03 houses in their respective renovation states between 2000 and 2050 for mineral wool insulation. The reason why results when applying vacuum insulation is shown is that these results are very similar to the corresponding insulation solution for mineral wool. The total energy consumption for heating purposes, also known as the energy reduction potential, will decrease during the simulation due to demolition of buildings representing the SFH03 stock segment. See Table 32 for an overview of the change in energy need for heating throughout the simulations.

As shown, the buildings in Rn1 represent the largest energy potential during the first 30 - 40 years in the simulation. However, with an increasing share of dwellings in Rn3, the corresponding heating demand for SFH03 buildings in Rn3 will increase throughout the simulation. In the baseline scenario of Figure 25, the heating demand for SFH03 buildings in renovation state Rn3 is higher from the year 2038 compared to the remaining dwellings in renovation state Rn2 and Rn1.

Even though the share of renovated dwellings in Rn3 increases during the simulation, the total energy need for heating among SFH03 houses decreases. The energy potential increases with the ambitiousness of the insulation solution (see Figure 25 - 27) and hence, scenario 4 (passive house standard, applying mineral wool insulation) results in a lower heating demand for SFH03 buildings in Rn3 than scenario 2 (TEK 10 standard applying mineral wool insulation) and the baseline scenario (historically refurbished, using mineral wool). In the baseline scenario in 2050, the heating demand for SFH03 buildings in Rn3 is 1 526 GWh. In scenario 2 and 4, the heating demand in 2050 has decreased to respectively 1 416 and 1 356 GWh.

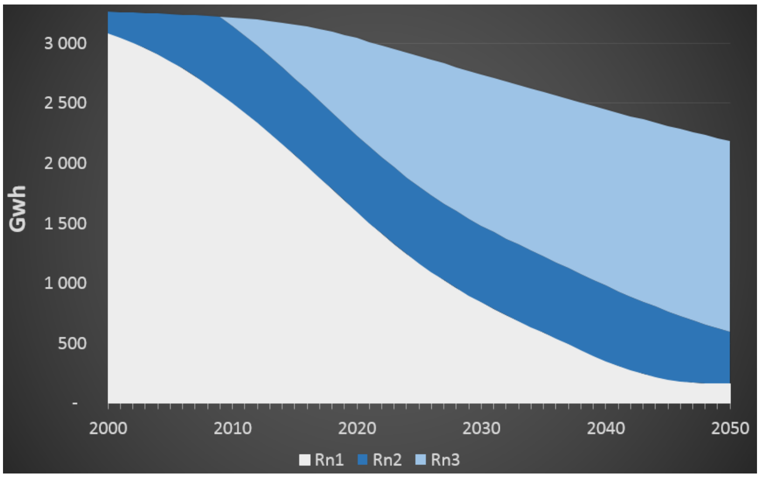


Figure 25: Energy composition of SFH03 in renovation state Rn1, Rn2 and Rn3. Baseline scenario (historical refurbishment). Renovation cycle of 40 years applied.

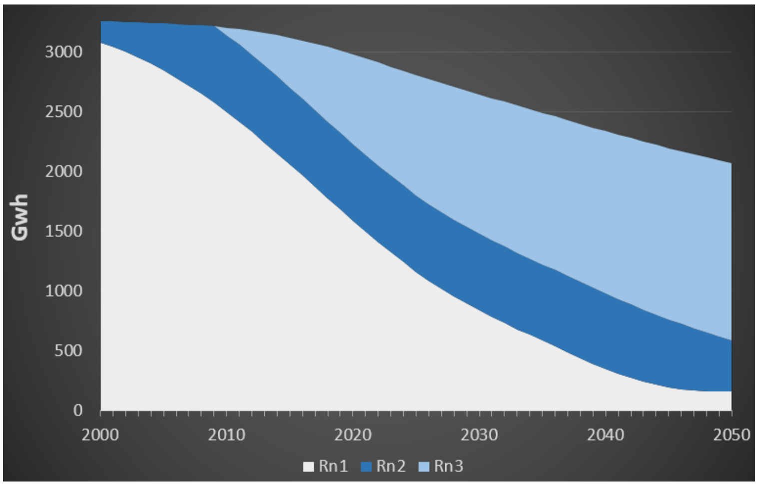


Figure 26: Energy composition of SFH03 in renovation state Rn1, Rn2 and Rn3, scenario 2 (min.wool, TEK10 standard). Renovation cycle of 40 years applied.

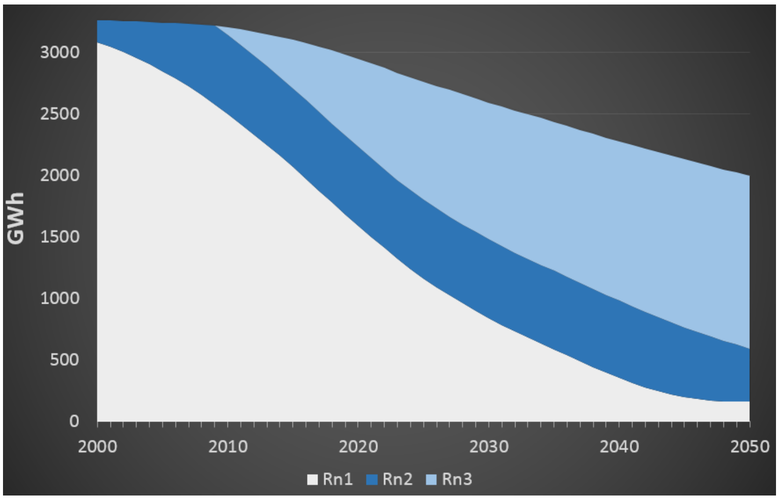


Figure 27: Energy composition of SFH03 in renovation state Rn1, Rn2 and Rn3, scenario 4 (min.wool, passive house standard). Renovation cycle of 40 years applied.

Figure 28 shows the change in heating demand in the SFH03 dwelling stock for all the insulation solutions in the scenario analysis. The baseline scenario is the scenario with the smallest energy potential. Yet, there is an energy potential of almost 32 % relative to the energy need for heating in 2000. Figure 28 also shows that the insulation solutions corresponding to a passive house standard yield better energy results than the TEK 10 solutions and the historical refurbishment.

Applying VIP insulation results in a slightly higher heating demand when approaching TEK 10 (scenario 3) and passive house standard (scenario 5) compared to applying mineral wool insulation. The difference in energy results between the scenarios increases with time. For instance, in 2010, the variance between scenario 2 and scenario 3 is 0.02 % and in 2050, the variance has increased to 0.05 % (see Table 31).

Table 32 shows the energy potential among the scenarios relative to the baseline scenario in 2010. Among the five scenarios, it is scenario 4, approaching passive house standard with mineral wool insulation, which has the biggest energy potential of -37.7 % in 2050 relative to the baseline scenario in 2010.

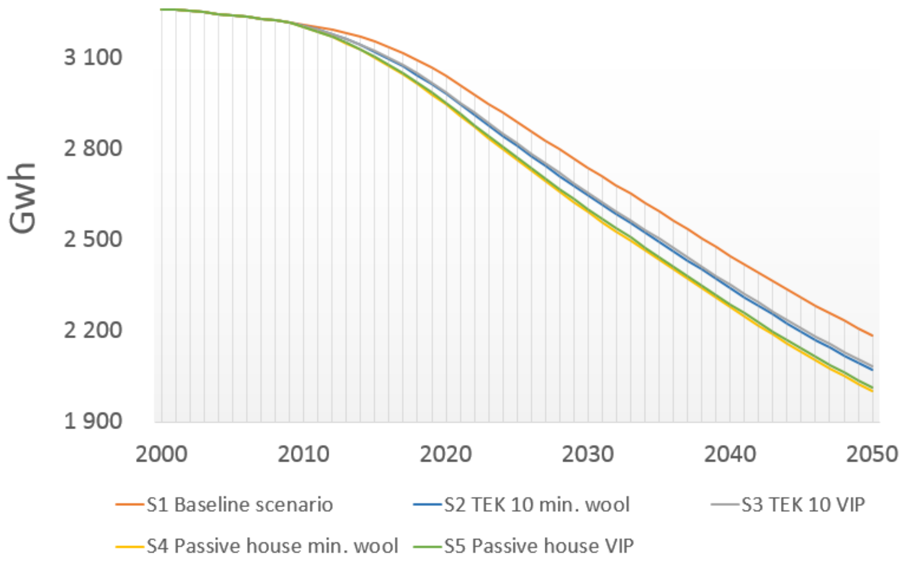


Figure 28: Total energy need for heating of SFH03 for the different scenarios in renovation state Rn3. Renovation cycle of 40 years applied.

Table 31: Energy potential when applying different renovation types for Rn3. Baseline renovation cycle of 40 years applied.

Year	*2010*	*2030*	*2050*
Scenario 1 BL [GWh]	3 214	2 739	2 185
Scenario 2	-0.15 %	-3.3 %	-5.3 %
Scenario 3	-0.13 %	-3.0 %	-4.8 %
Scenario 4	-0.24 %	-5.3 %	-8.5 %
Scenario 5	-0.23 %	-5.0 %	-7.9 %

Table 32: Energy potential when applying different renovation types for Rn3. The potential is measured relative to year 2010 for the baseline scenario. Baseline renovation cycle of 40 years applied.

Year	*2030, Δ2010 BL*	*2050, Δ2010 BL*
Scenario 1	-14.8 %	-32.0 %
Scenario 2	-17.5 %	-35.5 %
Scenario 3	-17.2 %	-35.2 %
Scenario 4	-19.2 %	-37.7 %
Scenario 5	-18.9 %	-37.3 %

Figure 29 and Figure 30 show the total energy need for heating for the SFH03 dwelling segment with renovation cycles of 50 or 30 years, with corresponding tables for the energy potential. The biggest energy potential when renovating every 30, 40 and 50 years relative to year 2010 (scenario 4) is respectively 34.9, 37.7 and 36.5 % (see Table 32, Table 34 and Table 36). It is interesting to observe that renovating the façade every 40 years results in a higher energy potential than renovating every 50 or 30 years. It is also interesting to see that even though the renovation cycle of 40 and 30 years resulted in equal renovation activity in 2050, the energy potential is quite different.

All five insulation solutions have an almost equal energy reduction in 2030 when refurbishing every 50 or 30 years. However, in 2010, the insulation solutions for the 50-year renovation cycle have a higher energy potential compared to the insulation solutions for the 30-year renovation cycle.

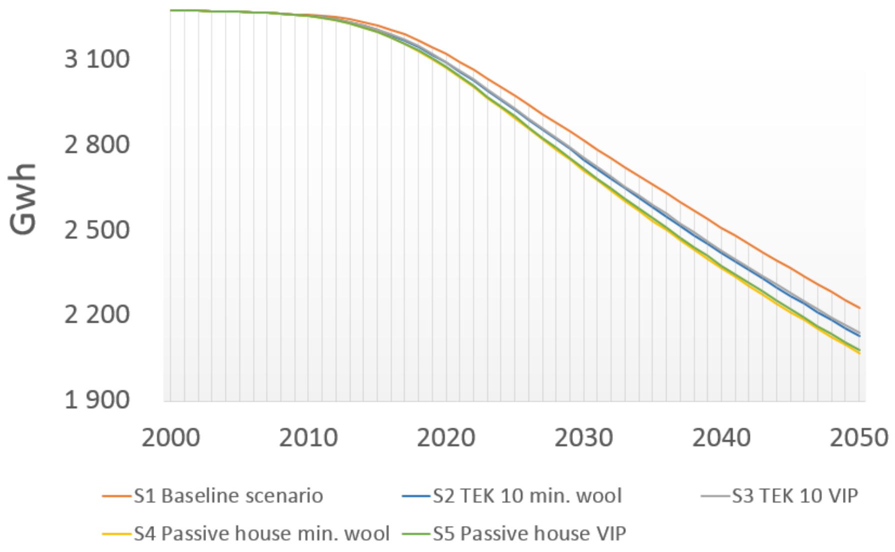


Figure 29: Total energy need for heating of SFH03 for the different scnearios in renovation state Rn3. Renovation cycle of 50 years applied.

Table 33: Energy potential when applying different renovation types for Rn3. Baseline renovation cycle of 50 years applied.

Year	*2010*	*2030*	*2050*
Scenario 1 BL [GWh]	3 256	2 816	2 228
Scenario 2	-0.06 %	-2.3 %	-4.5 %
Scenario 3	-0.06 %	-2.1 %	-4.0 %
Scenario 4	-0.10 %	-3.7 %	-7.2 %
Scenario 5	-0.09 %	-3.5 %	-6.7 %

Table 34: Energy potential when applying different renovation types for Rn3. The potential is measured relative to 2010 for the baseline scenario. Baseline renovation cycle of 50 years applied.

Year	*2030, Δ2010 BL*	*2050, Δ2010 BL*
Scenario 1	-13.5 %	-31.6 %
Scenario 2	-15.6 %	-34.7 %
Scenario 3	-15.4 %	-34.3 %
Scenario 4	-16.8 %	-36.5 %
Scenario 5	-16.6 %	-36.2 %

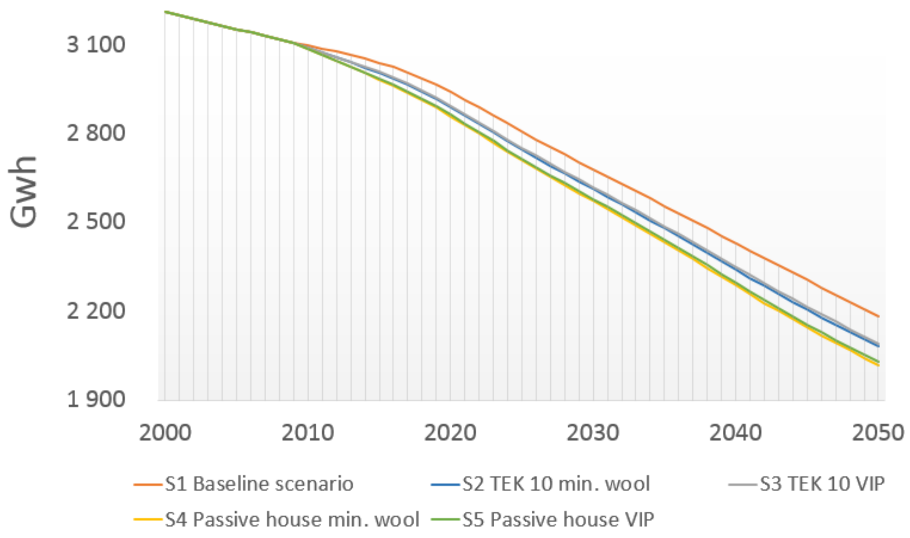


Figure 30: Total energy need for heating of SFH03 for the different scenarios in renovation state Rn3. Renovation cycle of 30 years applied.

Table 35: Energy potential when applying different renovation types for Rn3. Baseline renovation cycle of 30 years applied.

Year	*2010*	*2030*	*2050*
Scenario 1 BL [GWh]	3 096	2 677	2 185
Scenario 2	-0.24 %	-2.5 %	-4.8 %
Scenario 3	-0.22 %	-2.2 %	-4.3 %
Scenario 4	-0.38 %	-4.0 %	-7.7 %
Scenario 5	-0.36 %	-3.7 %	-7.2 %

Table 36: Energy potential when applying different renovation types for Rn3. The potential is measured relative to year 2010 for the baseline scenario. Baseline renovation cycle of 30 years applied.

Year	*2030, Δ2010 BL*	*2050, Δ2010 BL*
Scenario 1	-13.5 %	-29.4 %
Scenario 2	-15.6 %	-32.8 %
Scenario 3	-15.4 %	-32.5 %
Scenario 4	-16.9 %	-34.9 %
Scenario 5	-16.7 %	-34.5 %

Figure 31 shows the CO_2 level of the SFH03 stock segment during operation in the baseline scenario when assuming a renovation cycle of 40 years. Because the operational carbon emissions are dependent on the delivered energy, this graph has an identical shape to the energy graph of the baseline scenario, Figure 25. Thus, the share of carbon emissions from Rn1 and Rn2 are equal to the share of energy consumption from Rn1 and Rn2 in the time period between 2000 and 2050.

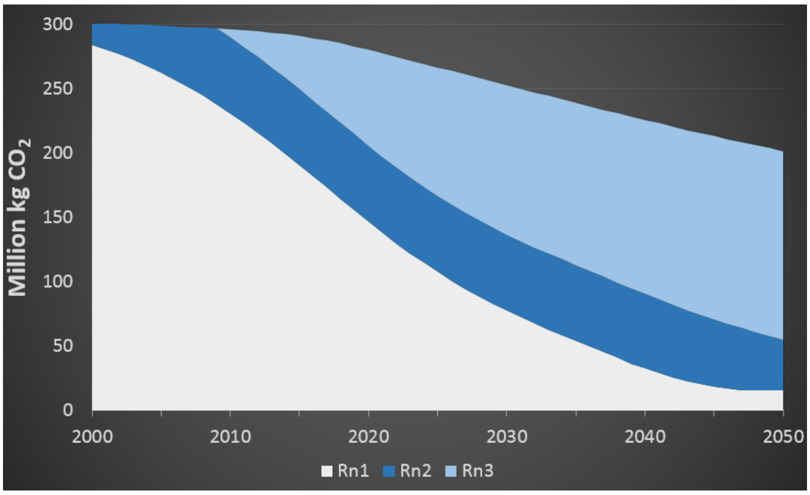


Figure 31: CO_2 emissions from SFH03 in renovation state Rn1, Rn2 and Rn3. Renovation cycle of 40 years applied [million kg CO_2 eq.].

Figure 32 shows the total carbon emission development for the different scenarios towards 2050 for all SFH03 dwellings during operation. As shown, and in coherence with Table 37, the CO_2 emissions in the baseline scenario are reduced from 318 million in 2010 to 216 million kg CO_2 eq. in 2050. This corresponds to a 32 % decrease in CO_2 emissions in 2050.

Figure 33 and Figure 34 show the CO_2 potential when renovation cycles of respectively 50 and 30 years are applied. An important observation is that the CO_2 potential follows the energy consumption of and renovation activity in the dwelling stock segment. This results in an almost identical CO_2 potential as the energy potential with a corresponding renovation cycle. Comparing Table 37 and Table 38 with Table 31 and Table 32 confirms this observation. This also applies for the scenarios with renovation cycles of 30 and 50 years.

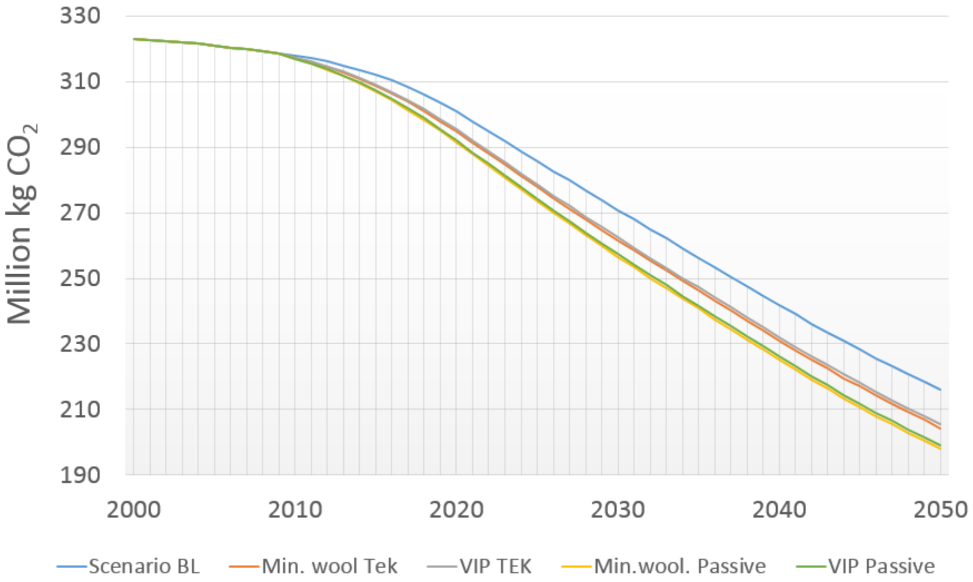


Figure 32: CO_2 reduction potential for the different insulation solutions in the scenario analysis. Renovation cycle of 40 years applied.

Table 37: CO_2 savings in the scenario analysis relative to CO_2 emissions for the baseline scenario in year 2010, 2030 and 2050. Renovation cycle of 40 years is applied.

Year	*2010*	*2030*	*2050*
Scenario 1 BL [million kg CO_2]	318	271	216
Scenario 2	-0.16 %	-3.4 %	-5.4 %
Scenario 3	-0.15 %	-3.1 %	-4.9 %
Scenario 4	-0.25 %	-5.3 %	-8.4 %
Scenario 5	-0.24 %	-5.0 %	-7.9 %

Table 38: CO_2 savings for all scenarios relative to CO_2 emissions in 2010 for the baseline scenario. Renovation cycle of 40 years is applied.

Year	*2030, Δ2010 BL*	*2050, Δ2010 BL*
Scenario 1	-14.8 %	-32.0 %
Scenario 2	-17.7 %	-35.7 %
Scenario 3	-17.4 %	-35.4 %
Scenario 4	-19.3 %	-37.7 %
Scenario 5	-19.0 %	-37.4 %

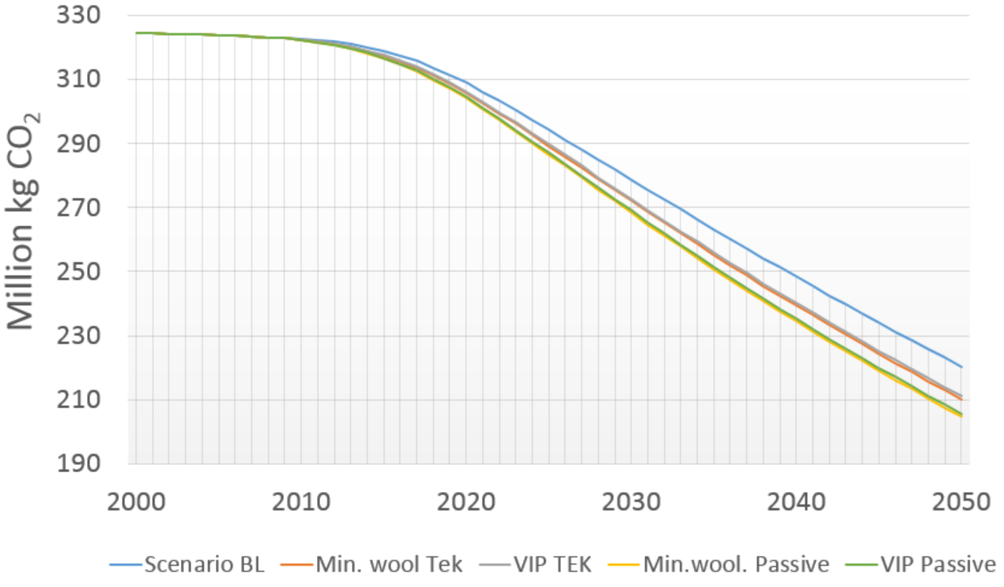


Figure 33: CO_2 reduction potential for the different insulation solutions in the scenario analysis. Renovation cycle of 50 years applied.

Table 39: CO_2 savings in the scenario analysis relative to CO2 emissions for the baseline scenario in year 2010, 2030 and 2050. Renovation cycle of 50 years is applied.

Year	*2010*	*2030*	*2050*
Scenario 1 BL [million kg CO_2]	323	279	220
Scenario 2	-0.06 %	-2.4 %	-4.6 %
Scenario 3	-0.06 %	-2.2 %	-4.2 %
Scenario 4	-0.10 %	-3.7 %	-7.0 %
Scenario 5	-0.09 %	-3.5 %	-6.7 %

Table 40: CO_2 savings for all scenarios relative to CO_2 emissions in 2010 for the baseline scenario. Renovation cycle of 50 years is applied.

Year	*2030, Δ2010 BL*	*2050, Δ2010 BL*
Scenario 1	-13.6 %	-31.7 %
Scenario 2	-15.7 %	-34.8 %
Scenario 3	-15.5 %	-34.5 %
Scenario 4	-16.8 %	-36.5 %
Scenario 5	-16.6 %	-36.2 %

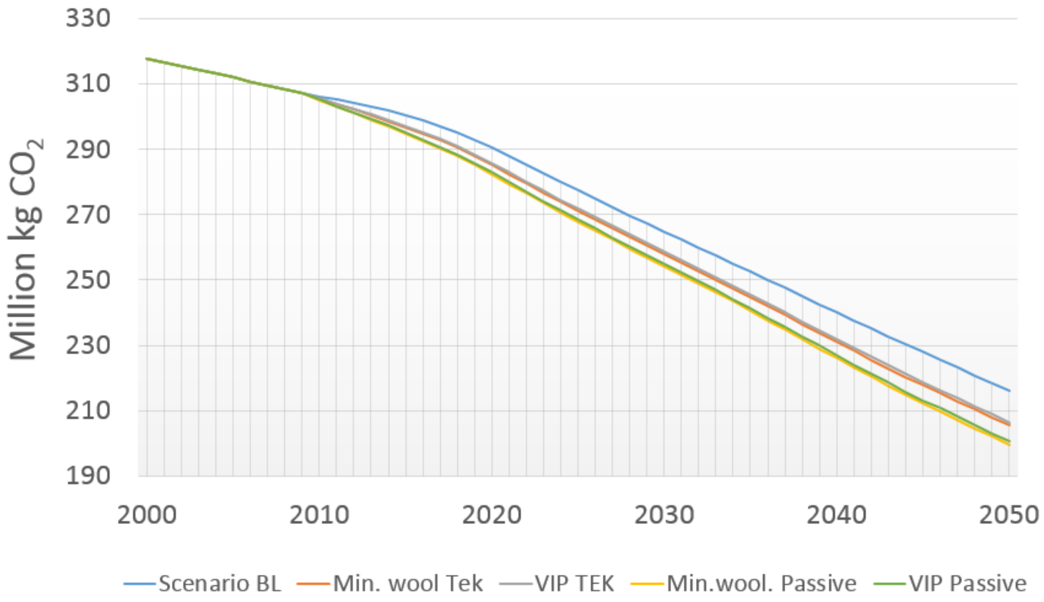


Figure 34: CO_2 reduction potential for the different insulation solutions in the scenario analysis. Renovation cycle of 30 years applied.

Table 41: CO_2 savings in the scenario analysis relative to CO_2 emissions for the baseline scenario in year 2010, 2030 and 2050. Renovation cycle of 30 years is applied.

Year	*2010*	*2030*	*2050*
Scenario 1 BL [million kg CO_2]	306	265	216
Scenario 2	-0.25 %	-2.6 %	-4.9 %
Scenario 3	-0.22 %	-2.3 %	-4.5 %
Scenario 4	-0.38 %	-4.0 %	-7.6 %
Scenario 5	-0.36 %	-3.7 %	-7.1 %

Table 42: CO_2 savings for all scenarios relative to CO_2 emissions in 2010 for the baseline scenario. Renovation cycle of 30 years is applied

Year	*2030, Δ2010 BL*	*2050, Δ2010 BL*
Scenario 1	-13.5 %	-29.5 %
Scenario 2	-15.8 %	-32.9 %
Scenario 3	-15.6 %	-32.6 %
Scenario 4	-17.0 %	-34.8 %
Scenario 5	-16.8 %	-34.5 %

4.4 Sensitivity analysis

Table 43 and Table 44 present the results from the sensitivity analysis when changing the respective parameters from ±15 to ± 70 %. The variables, except for the indoor temperature, are scaled with similar values in order to compare the sensitivity in energy need for heating. Table 44 shows the sensitivity analysis for the indoor temperature when the temperature ranges from 17 to 23 °C. The symbol ΔQ_b represents the change in annual heating demand when changing the respective input parameter to a specified value.

Table 43: Results from sensitivity analysis

	ΔQ_b, tb	ΔQ_b, n_{50}	ΔQ_b, n_{inf}	ΔQ_b, V	ΔQ_b, α_{frame}
– 15 %	-1.3 %	- 3.8 %	- 1.3 %	- 3.6 %	- 0.9 %
+ 15 %	+1.3 %	+ 4.1 %	+ 3.0 %	+ 3.9 %	+ 1.2 %
– 25 %	-1.9 %	- 5.7 %	- 2.5 %	- 5.8 %	- 1.6 %
+ 25 %	+1.9 %	+ 6.5 %	+ 4.7 %	+ 6.7 %	+ 1.9 %
- 35 %	-3.2 %	- 7.7 %	- 3.5 %	- 7.7 %	- 2.3 %
+ 35 %	+3.2 %	+ 9.5 %	+ 6.5 %	+ 9.5 %	+ 2.7 %
- 70 %	-5.8 %	-11.8 %	- 7.6 %	- 11.8 %	- 4.7 %
+ 70 %	+5.7 %	+ 19.6 %	+ 12.5 %	+ 19.6 %	+ 5.3 %

Table 44: Results from sensitivity analysis for the room temperature parameter, ϑ [°C]

ϑ	ΔQ_b
- 5.3 % (19 °C)	- 7.1 %
+ 5.3 % (21 °C)	+ 7.4 %
- 10.5 % (18 °C)	- 14.1 %
+ 10.5 % (22 °C)	+ 15.3 %
- 15.8 % (17 °C)	- 20.7 %
+ 15.8 % (23 °C)	+ 23.5 %

Figure 35 presents the variance in energy need for heating when changing the indoor temperature, ϑ [°C], from the default value of 20°C to ± 3°C. Among all of the variables used in the sensitivity analysis, the indoor temperature has the largest variations and is the most sensitive parameter to changes, ranging from + 23.5 and – 20.7 % of the annual heating demand when changing the indoor temperature with ±15.8 %. In addition, the change in indoor temperature results in a larger change in annual heating demand. This did not occur for any of the other variables used in the sensitivity analysis.

Figure 36 presents the variance in annual heating demand for different values of the normalized thermal bridging value. As shown, the fluctuations in annual heating demand are not significantly high. Even when changing the normalized thermal bridging factor with ± 70 %, the annual heating demand has a change of less than 6 %.

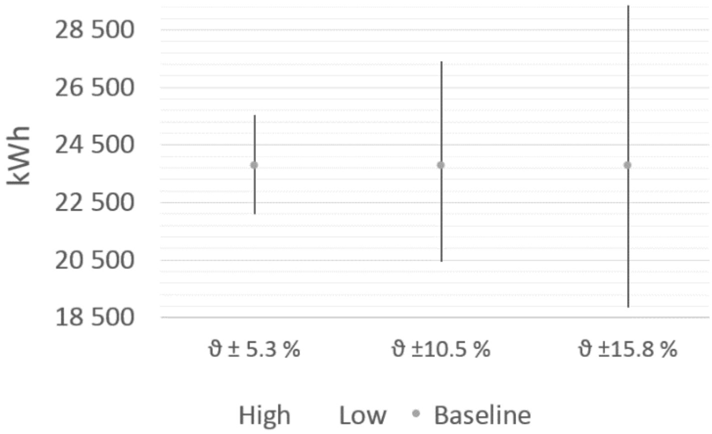


Figure 35: Sensitivity analysis of the average indoor temperature, ϑ [°C].

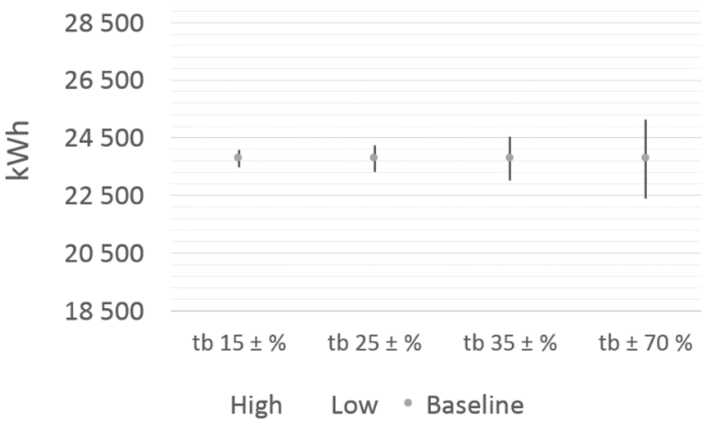


Figure 36: Sensitivity analysis of the normalized thermal bridging value, tb [W/m^{2}K].

Figure 38 and Figure 37 show the fluctuations in the energy need for heating when changing the air leakage rate, n_{50} [1/h], and the natural ventilation rate, n_{inf} [m^3/hm^2]. It is clear from the graphs that the air leakage rate is far more sensitive than the natural infiltration in the building, with an increase of almost 20 % in annual heating demand when changing the leakage number by 70 %. In comparison, the natural infiltration rate is increased by almost 13 %, which is 7 % less than the air leakage rate. However, both of the parameters result in significant fluctuations in the heating demand of the building.

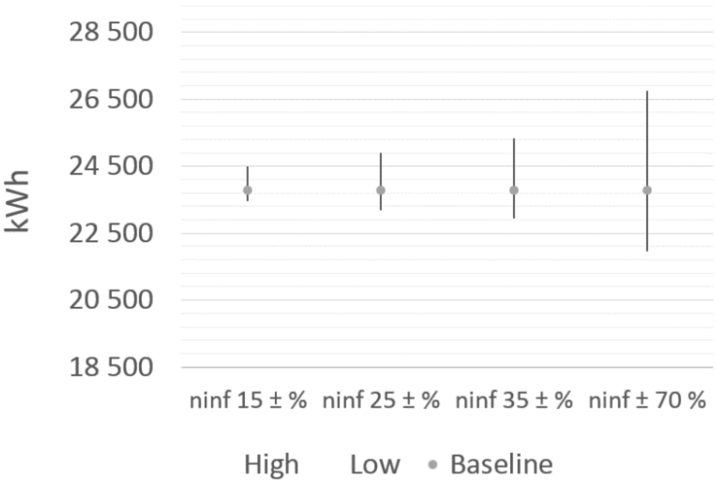


Figure 37: Sensitivity analysis of n_{inf} [m^3/hm^2]

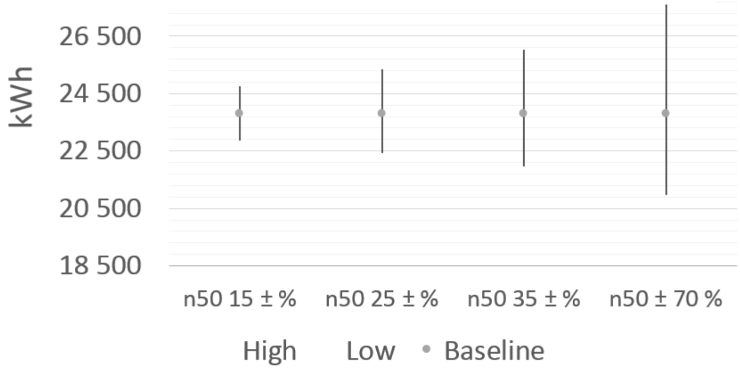


Figure 38: Sensitivity analysis of n_{50} [1/h].

Figure 39 and Figure 40 show the fluctuation in heating demand when changing the conditioned building volume and the frame/window ratio. The volume is a sensitive parameter, changing the annual heating demand with almost 20 % when the parameter is changed to 70 %. Figure 39 shows that the conditioned building volume parameter and the leakage number, n_{50}, changes the heating demand to almost the same extent. Figure 40 shows that the variable representing the frame/window ratio has little influence on the annual heating demand. This is in accordance with Table 43, which show that α_{frame} and the normalized thermal bridging factor, tb, are the least sensitive parameters in this sensitivity analysis.

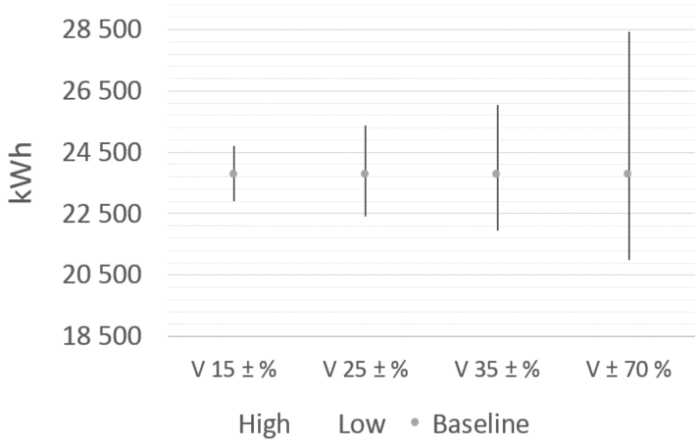


Figure 39: Sensitivity analysis of the heated building volume, V [m3].

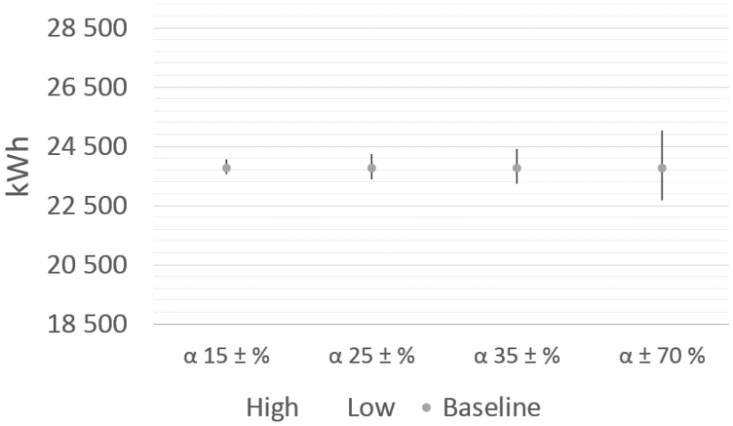


Figure 40: Sensitivity analysis of the frame/window ratio, α_{frame} [-].

5. Discussion

In this chapter, I will provide a discussion of the main findings of the study and what appear to be their causes, referring to the two research questions stated in chapter 1. From this, it is elaborated on the strengths and weaknesses of the methods and models used in the study. Finally, implications of the findings are presented with respect to possible messages for policy-making and further research.

5.1 Main findings of this study

5.1.1 Façade renovation measures for one SFH03 building

Energy need for heating

In this master's thesis, more advanced insulation solutions for façade refurbishment have been introduced. As can be seen from Figure 18, the SFH03 building achieves energy savings in heating demand, which vary between 14 and 30 kWh/m^2 heated floor area, depending on the insulation solution applied.

The vacuum insulation (VIP) yields a slightly higher heating demand than mineral wool insulation for TEK 10 and passive house requirements of respectively 1 and 2 kWh/m^2. This is because the insulation materials approach passive house and TEK 10 standards by using a standard insulation thickness that corresponds to the requirements. For the vacuum insulation materials, this resulted in one (Dow corning) fulfilling the requirements and the other (Microtherm) having a slightly higher U-value than the U-value requirements.

Figure 18 and Figure 19 show that the SFH03 building's annual heating demand in original state is 23 104 kWh, corresponding to 152 kWh/m^2 per heated floor area. According to the barrier study by Prognosesenteret & Entelligens (2011), an average single-family house built in the 1970s has an annual heating demand of 87.8 kWh/m^2. This is substantially lower than the findings from the energy audit in this master's thesis. The discrepancy may partly be explained with the different stock segments examined. Prognosesenteret & Entelligens (2011) have measured the average heating demand of all SFH03 buildings, regardless of the building's renovation state. Hence, they have not distinguished between single-family houses in an original state and refurbished houses like in this master's thesis. Typical refurbishment measures conducted on the refurbished SFH03 dwellings may be façade refurbishment, changing the windows or installing a balanced ventilation system. In addition, the SFH03 building utilized in the energy audit by Prognosesenteret & Entelligens (2011) has some different building characteristics from the ones used in this master’s thesis, something which also results in a discrepancy in heating demand.

Even though there is a significant energy saving potential related to refurbishing the outer walls and adding supplementary insulation, this energy measure might not be suitable as the only energy measure for all dwellings. Occasionally, the building envelope might get too air tight when adding supplementary insulation, resulting in a worse indoor climate. According to SINTEF Fag (2014b), it might be necessary to install a balanced ventilation system in addition to refurbishing the outer walls in order to sufficiently remove moist air and increase the air exchange rate.

Delivered energy

The delivered energy to the SFH03 building depends on the energy efficiency of the energy carriers chosen and the respective energy share delivered from each energy carrier. In this thesis, the energy carriers were chosen to be bio wood and electricity, as these are common energy carriers for single-family houses built in the 1970s. The efficiency factors utilized are taken from TABULA, which utilizes general values for all European countries participating in the project. An energy efficiency of 0.64 for bio wood and 1 for electricity, amounts to 163 kWh/m^2 in delivered energy to the SFH03 building for heating purposes.

In coherence with the NS3031:2014 methodology, the overall energy efficiency is calculated based on the three factors: The production efficiency, the distribution efficiency and the special effect in the conditioned room. Based on this methodology, the recommended values for energy efficiency of bio wood and electricity are lower than the standard values in TABULA of respectively 0.52 for bio wood and 0.89 for electricity. By using the recommended values in NS3031:2014, the calculated delivered energy would be higher than the results in Table 25 and Table 27. One may question if the recommended values in NS3031:2014 fit better for Norwegian conditions by yielding more realistic results for the delivered energy than by using standard energy efficiency factors from TABULA.

Primary energy

The primary energy is dependent on the delivered energy and the primary energy factors called PEFs. Even though the PEF for electricity accounts for import and export to the grid, there lies an uncertainty in the future PEF value for electricity, as the future export and import demand to the power grid is unknown. The primary energy of the example building today may be quite different from the primary energy in 2050. Considering that Norway will be connected to the grid in the UK and the rest of Europe through the NSN Link (Statnett, 2013b) and NordLink project (Statnett, 2013a), it is not unrealistic to assume that the future PEF for electricity in Norway will increase in the upcoming decades due to an increase in electricity import from carbon based energy carriers.

Carbon emissions

Since the carbon emissions only are dependent on the energy usage in the SFH03 building, the emissions are dependent on the delivered energy and the CO_2 coefficients utilized. As previously mentioned, there is an uncertainty related to the results for delivered energy, and thus, the results for the operational carbon emissions.

The CO_2 coefficients for Norwegian conditions, taking into account the export and import of electricity, are updated this year and taken from “Klimakalkulatoren” (Klimaløftet, 2012). Therefore, one may assume that these coefficients are representative for Norwegian households.

Waste

The input data concerning share of manufactured insulation material going to waste is provided from only one person in the construction industry (Martinsen, 2015). This makes the assumption unreliable, and further mapping of the upstream material flows for refurbishment is needed.

In addition, it is an uncertain assumption that all original insulation is replaced with new insulation. According to Leraand (Rockwool, 2015), there is a large variation in the original insulation quality for single-family houses in the 1970s, and it is not possible to state an average amount of waste from original wall insulation. Some houses have 100 % intact insulation and only needs to add the extra amount of insulation required, and other houses have severally damaged insulation.

The total waste quantity from original and manufactured insulation has a direct impact on all of the KPIs in the material analysis in terms of calculating for a larger amount of insulation than necessary.

Material consumption

Even though VIP panels have a density that is more than 8 times higher than mineral wool insulation, the material consumption, hence the weight of the material required, for the different insulation solutions are almost identical. This is because the U-value requirements for TEK 10 and passive house standard corresponds to very thin thicknesses for the VIP insulation and hence a smaller total volume of insulation material than for mineral wool insulation. If waste of VIP panels was assumed when renovating the façade, there would be a bigger difference in material consumption between the two materials.

Upstream flows

When adding supplementary insulation to the outer walls, the upstream flows from carbon emissions and energy consumption increase. VIP insulation is in particular a material with high upstream energy and carbon emissions. However, with the façade refurbishment, there will be significant energy savings and reduced carbon emissions that will last until the next façade refurbishment, and these will outweigh the high upstream flows. According to Prognosesenteret & Entelligens (2011) and SINTEF Fag (2014b), the expected lifetime for building facades is 40 years, so this is the assumed baseline value for the amount of years between façade refurbishments for SFH03 buildings.

The insulation solution emitting the most CO_2 during manufacturing and that requires the highest upstream energy consumption is VIP insulation fulfilling passive house requirements. The upstream energy required to manufacture the material amounts to 528 kWh/m^2 floor area, corresponding to CO_2 emissions equal to 93 kg CO_2 eq. $/m^2$. The annual energy benefit and carbon emission reduction from upgrading from original state to VIP passive house standard correspond to 29 kWh/m^2 and 3 kg CO_2 eq. $/m^2$. In 40 years, the total energy savings is 1 160 kWh/m^2, corresponding to a carbon emission reduction of 120 kg CO_2 eq. $/m^2$. Hence, the total energy savings are clearly higher than the upstream energy flow, and the reduction in carbon emissions and upstream CO_2 flow. All other insulation solutions will result in higher energy savings and a higher carbon emission reduction.

The transport stage from factory to construction site is included when calculating the upstream flows in the material analysis. However, according to a study from SINTEF Fag (2014a), the transport stage does not have a large impact on the results of energy and carbon emissions in the life cycle analysis of insulation materials. The transport is not significant, even if the factory producing insulation materials was based outside of Norway (SINTEF Fag, 2014a). Rockwool and Glava are produced in Norway, so the energy required to transport the insulation to a construction site in Norway is small. Microtherm and Dow Corning insulation on the other hand are produced in Denmark and Belgium respectively, and would require more energy for transportation to the construction site. It may therefore have been unnecessary to include the transport stage in the material analysis, concerning a small energy consumption and low carbon emissions compared to the other stages in the material life cycle.

Investment costs

The baseline interest rate is set to 5 % from a policy perspective and applies between a private company and the national base rate in Norway. However, the investors in this context are private households and not companies. It is reasonable to believe that a payback time of 40 years for a façade refurbishment is a little too long. By increasing the interest rate, the payback time decreases. Results show that even with an interest rate of 7 % all mineral wool solutions yield a positive NPV and hence, are economically viable.

A critical parameter influencing the economic analysis is the energy price, as the future energy price is uncertain. The sensitivity analysis of the energy price show that even with a 100 % decrease in energy price, all insulation solutions for mineral wool are economically viable due to a low investment price and high energy savings.

Another variable influencing the economic results is the investment price for insulation materials. Concerning mineral wool insulation, Leraand (2015) in Rockwool states that the average discounts on insulation materials were 9 % in addition to 25 % taxes. A former master's student has presented prices for Rockwool insulation [NOK/m^2 outer wall], provided from Hjellnes Consulting (Storvolleng, 2014). These prices coincide well with the assumption from Leraand (2015). For instance, Hjellnes pays 74.3 NOK/m^2 wall for an insulation thickness of 0.198 m, which is the corresponding insulation thickness when approaching TEK 10 standard. The average price for the same product is, according to Leraand, 75.7 NOK/m^2 wall, hence almost equal to the price provided by Hjellnes, with a 2 % higher price. It is therefore fair to assume that the investment costs used for mineral wool insulation in the cost analysis is less uncertain than the energy price and interest rate.

The investment costs when applying mineral wool for historical refurbishment and refurbishment corresponding to TEK 10 standard are much lower than for refurbishment corresponding to passive house standard. Upgrading to TEK 10 standard gives a 13 % increase and upgrading to passive house standard results in a 240 % increase in investment cost compared to a historical refurbishment. The higher price difference between upgrading to passive house and TEK 10 standard is due to the fact that there are no mineral wool products with an insulation thickness corresponding to passive house standard (350mm). Instead, one purchases two insulation mats that in total have the required thickness (200mm + 150mm). Insulation products value more or less the same regardless of insulation thickness. When applying two insulation mats for the same surface area, this will therefore result in a significant increase in investment costs.

The VIP insulation manufacturers were hard to get in touch with, and I could only receive a price estimate from Promat international, which manufactures Microtherm insulation. Furthermore, VIP is a new insulation product that is not much used by Norwegian contracting firms. This enables manufacturers and retailers to charge more and vary the prices for the same product. Little data and the fact that VIP is a new insulation product in Norway make the investment price for VIP an uncertain variable in NPV calculations. Therefore, it is not certain if a positive NPV for VIP when approaching TEK 10 level reflects the actual NPV value.

5.1.2 Influence of façade renovation measure on the aggregated heating demand and carbon emissions for the Norwegian SFH03 building stock segment towards 2050

Renovation activity for the SFH03 housing segment towards 2050

There are significant variations in renovation activity throughout the simulation period for the SFH03 stock segment. This is because the SFH03 buildings in the residential stock follows an average time span between façade renovations. Hence, more SFH03 buildings are renovated in the period where façade replacement is needed, hence when approaching the lifetime of the façade, and fewer during the first decades after façade refurbishments.

The slope of the line graph is higher when the renovation activity is high and lower in periods when less façade refurbishments are conducted. Hence, the point on the line graph with the highest renovation activity implies that this is the year where it is expected that most SFH03 buildings refurbish the façade. Figure 24 shows the renovation activity for the different renovation cycles from the year 2010 – 2050, where the slope of the line graph corresponds to the renovation activity for the respective renovation cycles. As shown, the steepest slope of the line graphs occur in different years in the simulation, respectively year 2010, 2020 and 2030 for the 30-, 40- and 50- year renovation cycle. This is because the average time between façade refurbishments differs due to different input values in the model for the average lifetime of the façade.

Energy potential

High uncertainty in defined indoor temperature results in an uncertain energy result for space heating with the different façade refurbishment solutions for the SFH03 building. When there is uncertainty in the energy intensity from the SFH03 building, the up-scaled results to dwelling stock level are also related with uncertainty. However, ongoing studies by Sandberg show that the total energy need in the Norwegian housing stock are similar to the available statistics on energy usage in the housing stock. According to Sandberg and Brattebø (2012), about 50 % of the total energy need is from space heating, hence, there is reason to believe that when the results from the long-term modeling are similar to statistics, it shows that the assumptions defining the heating demand are not too far from the reality.

The reduction potential in heating demand of the SFH03 dwelling stock is significant for all insulation solutions. Even for the baseline scenario, which achieves the lowest reduction in energy consumption, the total heating demand in 2050 is reduced by almost 1/3 relative to the total heating demand in 2010 for all renovation cycles. The large energy potential is however highly due to demolition of a larger share of the dwellings.

Among the three renovation cycles, refurbishing the façade every 40 years results in the biggest energy potential at all times in the simulation period. A large share of the SFH03 dwelling stock is renovated after 2010, hence, are in Rn3, and achieves a significant energy reduction when refurbishing to a more ambitious level than historical refurbishment. Among the different scenarios corresponding to the respective façade refurbishments, whereas scenario 4 (fulfilling passive house standard requirements with mineral wool insulation) gives the biggest energy minimization at all times in the simulation period.

However, there are variations in energy reduction depending on the average time between façade refurbishments. The SFH03 dwelling stock segment following the 30-year renovation cycle yields an energy potential that is almost 3 % lower than for the 40-year renovation cycle, despite achieving the same renovation share at the end of 2050 in Rn2 and Rn3. The large share of dwellings renovated before 2010, hence dwellings in Rn2, may explain the higher future heating demand. When a large amount of SFH03 buildings are renovated to a less ambitious renovation state than the façade refurbishment conducted after 2010, this may yield an "energy lock-in" effect until the next façade refurbishment for the respective dwellings. This is because the large share of the dwellings in Rn2 are forced to be in this renovations state for the next 30 years.

Despite historically refurbished dwellings save 14 kWh/m^2 in heating demand compared to SFH03 dwellings in an original state, all other insulation solutions give annual energy savings that are 23 kWh/m^2 or higher. This implies that historically refurbished dwellings consume 9 kWh/m^2 more energy, corresponding to 39 % less in energy savings, than dwellings that are renovated to a more ambitious level. Hence, for all other scenarios than the baseline scenario, where Rn2 and Rn3 have an equal heating demand, the SFH03 segment will have a significantly lower heating demand. Moreover, the larger share of dwellings constituting Rn3 instead of Rn2, the higher is the energy potential achieved in 2050. By way of comparison, the share of renovated dwellings is equal when renovating every 30 or 40 years. The difference is that a significantly larger share of SFH03 buildings are in Rn2 when renovating every 30 years, and this yields a larger heating demand than if they were renovated to a more ambitious renovation state. This shows that the insulation solution applied influences the energy potential more than the actual renovation frequency.

Furthermore, the energy potential relative to 2010 in the baseline scenario is higher for dwellings following a 40-year renovation than a 30-year renovation cycle despite the fact that the share of renovated SFH03 buildings in 2050 are equal for both renovation cycles. This is because the heating demand in 2010 is higher when refurbishing every 40 years than every 30 years. When the heating demand in 2050 is equal for both renovation cycles, this results in higher energy savings relative to 2010 for the dwellings following the 40-year renovation cycle.

Carbon emission reduction potential

The operational CO_2 emissions from the SFH03 houses are dependent on the delivered energy to the dwelling stock segment. This is clear from equation 7, where the carbon emissions are equal to the delivered energy multiplied by a CO_2 coefficient for the respective energy carrier. Since the CO_2 coefficient is a scalar, the carbon emission potential is equal to the energy potential for the different insulation solutions with corresponding renovation cycles.

As mentioned in chapter 5.1.1, in Upstream flows, the carbon emissions from manufacturing insulation materials constitute a small part compared to the significant energy savings over a period equal to the façade lifetime. This is also the case for dwellings that go through façade refurbishment more than once during the simulation period. Due to limited time, it was not possible to calculate the exact benefits in carbon emission reduction for the SFH03 dwelling stock.

5.2 Strengths and weaknesses of methods and models used in this study

Two energy audit models and one dynamic stock model have been utilized in this study. The energy audit models are based on different calculation methods, as SIMIEN simulates dynamically and TABULA stationary. Different methodology is not an actual weakness to the respective models, but may be a weakness when validating the energy results by comparing the model results. In the following subchapter, I will discuss some of the reasons behind different energy results in SIMIEN and TABULA. In addition, there will be discussed weaknesses and strengths of the dynamic building stock model.

5.2.1 The SIMIEN and TABULA Model

SIMIEN is a well-known and utilized energy audit tool when examining the energy performance of buildings. The software fulfills the requirements to accuracy when measuring the energy balance, with good scores when comparing the model results to reference values (Programbyggerne, 2014b). It is therefore a clear strength to use SIMIEN in the energy audit in this master’s thesis as a method to validate the results from the TABULA worksheet.

Climate data

Some dynamic parameters in SIMIEN are not possible to change and will yield different energy results within the SIMIEN and TABULA model. For instance, this applies to the climate data for irradiation and outdoor temperature throughout the year. In TABULA, the climate data is set static on a monthly basis concerning irradiation and outdoor temperature. This results in differences between indoor and outside temperature throughout the year in SIMIEN and TABULA. Furthermore, it will have an impact on the results for the heating demand, as this is dependent on this temperature difference, the heat loss coefficient, the heating season duration and the heat gains.

Heat loss from the floor

One weakness when comparing heating demand results from SIMIEN and TABULA is that they have different methods of treating the U-value of the floor when the floor borders to an unheated basement and not the ground. The different heat loss calculations through the floor results in different heat losses through the floor within the two models.

When the floor is on top of an unheated basement, the room temperature will be higher than if the floor is on top of the ground. For this this reason, the transmission losses from the floor will be smaller.

In the TABULA methodology, an adjustment factor is utilized when the floor borders to an unheated basement. The standard value for this is 0.5, and hence, when applying this factor, TABULA yields a heat loss through the floor which is half of the heat loss compared to if the floor was on top of the ground. SIMIEN calculates a transmission loss through the ground which is almost the double of the heat loss calculated in TABULA. However, the difference in heating demand is not significant, as the total difference between the two models for heat loss through the floor only amounts to 3 %.

Ventilation heat loss

The TABULA calculation method presented in Loga and Diefenbach (2013), operates with four different air change rates caused by infiltration, differing from 0.05 – 0.4 1/h. In addition, the TABULA method uses an additional term when calculating the heat loss caused by infiltration of a building, representing usage of the building. This results in a different equation measuring the heat transfer coefficient by infiltration from the one used in SIMIEN, and thus NS3031:2014 (Standard Norge, 2014).

Results from the sensitivity analysis in SIMIEN

A sensitivity analysis in SIMIEN gives an indication of whether the methodology utilized when finding the energy balance of a building is robust given uncertainty and assumptions.

The sensitivity analysis in SIMIEN shows that there are particularly four parameters influencing the annual heating demand of the building. These are the conditioned building volume, the natural ventilation, the air leakage rate and the indoor temperature.

The conditioned building volume, V, and the natural ventilation, $n_{air,inf}$, influence the heat loss due to infiltration directly, as these constitute variables in the equation determining the infiltration heat loss. In coherence with NS3031:2014, the natural ventilation due to infiltration and the conditioned volume are proportional to each other (see equation 2). Since the natural ventilation and the air leakage rate are proportional (see equation 3), this explains why a specified change [%] in the air leakage rate, n_{50}, and V results in an almost identical change in heating demand. The equation calculating the infiltration heat loss is as follows (Standard Norge, 2014):

$$H_{inf} = cnV \qquad 2$$

H_{inf} *Heat loss coefficient for infiltration [W/K]*
$n_{air,inf}$ *Natural ventilation in the building [1/h]*
V *Conditioned building volume*
c *Specific heat capacity for air. Standard value = 0.33 [Wh/m^{3}K]*

When assuming no mechanical ventilation, the equation defining the natural ventilation due to infiltration is as follows (Standard Norge, 2014):

$$n = n_{50}e \qquad 3$$

n_{50} *Air leakage rate when the reference pressure in the building is 50 Pa [1/h]*
e *Terrain shielding coefficient. Standard value when no shielding = 0.1 [-]*

The indoor temperature is the most sensitive parameter in the sensitivity analysis and minor changes of the variable give significant fluctuations in the heating demand. It did not make sense to vary the indoor temperature to ± 70 %, as for the other variables, because this is not a realistic temperature span in an average household. Instead, ϑ varies ± 3 °C from the baseline indoor temperature of 20 °C. Since the indoor temperature is one of the variables defining the total heat loss of a building, this may explain the large changes in heating demand. See equation 4 below for total heat loss of a building in month i (Standard Norge, 2014):

$$Q_{H,i} = (H_D + H_U + H_v + H_{inf})(\vartheta - \vartheta_{out,i})t_i + Q_{g,i} \qquad 4$$

$Q_{H,i}$ *Heat loss from a building in month i [kWh]*
H_D *Direct transmission loss [W/K]*
H_U *Transmission loss to unheated zones in the building [W/K]*
H_V *Heat loss coefficient for ventilation [W/K]*
H_{inf} *Heat loss coefficient for infiltration [W/K]*
t_i *Amount of hours in month i divided by 1000 for conversion to kWh [h]*
$Q_{g,i}$ *Heat loss to the ground in month i*
ϑ *Indoor room temperature [°C]*
ϑ_{out} *Average outdoor temperature in month i [°C]*

As shown, the heat loss from a building is dependent on the respective heat loss coefficients, the difference in indoor and outdoor temperature, also known as ΔT, and the amount of hours measuring the heat loss. Climate data defining the outdoor temperature is gathered from years of statistical data within both of the models. Hence, the unknown variable defining ΔT is the indoor temperature, and a slight increase of the indoor temperature will result in a significant change of the total heat loss of the building. The heat loss to the ground, $Q_{g,i}$, is also dependent on the indoor temperature, but has in addition a more complex equation than the other heat loss sources. This term is therefore defined as a separate equation term in equation 4. In addition to the room temperature being a sensitive parameter, its baseline value is associated with significant uncertainty (Prognosesenteret & Entelligens, 2011).

Figure 17 shows that the biggest heat loss sources in the SFH03 building are the windows, walls and ventilation/infiltration. The thermal bridging factor and the window/frame ratio did not give as significant fluctuations in the energy need for heating as the three parameters mentioned previously. Considering that surcharge on the thermal bridges represents only 7 % of the total heat losses, and that the window frame area contributes to a minor change in solar heat gains, the sensitivity analysis yields a reasonable result.

The large fluctuations in heating demand when changing the volume, air leakage rate, natural ventilation and indoor temperature may be due to these variables being a part of critical equations determining the heat loss. Furthermore, the heating demand is equal to the total heat loss subtracted by the total heat gain; hence, the heat loss represents a large part of the heating demand.

The utilized SFH03 example building in the energy audit

The example building used in the thesis work is a synthetic average building taken from the EPISCOPE's typology brochure and hence, when the floor area is scaled up to stock segment level, the total floor area of SFH03 buildings matches statistical data. However, one may question if the chosen SFH03 building is a representative candidate of the SFH03 dwelling stock segment concerning geometry and technical characteristics. However, the SFH03 synthetic average building is very similar to a single-family house constructed in the 1970s, used in a study in the SEOPP report (SINTEF Fag, 2014b). Furthermore, according to Skeie et.al. (2014b), the building utilized in this study is typical for single-family houses constructed between 1971 and 1980.

Energy decay

The building data are assumed to be identical to those of the construction year. However, one may question if these characteristics have been maintained throughout decades without the building going through an energy decay. For instance, the U-value of the outer walls is of special interest in this master's thesis. Originally, the U-value of the outer walls were $0.41 W/m^2K$ in the 1970s when the building was constructed. If the current U-value in reality is higher, this would imply that the energy results for heating demand is better than the actual energy need for heating of today. Furthermore, façade refurbishment would yield higher energy savings, and thus a lower payback time of the investment of insulating the outer walls.

Not only may an energy decay or natural ageing occur with the original building, but by adding VIP insulation to the outer walls, there is a risk of perforating the material. If the panels are perforated, for example by a short object like a nail, the thermal conductivity may increase to almost the double of 20 mW/mK. Furthermore, there is a natural ageing of VIP materials, where the thermal conductivity increases between 4 and 8 mW/mK (Haavi & Jelle, 2012). This implies that there are more downsides concerning a decay in thermal characteristics of VIP panels compared to mineral wool insulation.

Indoor temperature

According to Prognosesenteret & Entelligens (2011), the difference between indoor and outdoor temperature during the coldest days of the heating season is the most crucial variable defining the heating demand of a building. Since there is sufficient historical data to define the outdoor temperature in Norway, the most important variable between the two temperatures is the indoor temperature. NS3031:2014 recommends a weighted average indoor temperature of 20.33 °C for all households (Standard Norge, 2014). However, Entelligens found that the average indoor temperature for single-family houses ranged from 18.0 °C to 20.4 °C after having conducted energy audits for 100 dwellings. The average room temperature for SFH03 buildings was found to be 19 °C (Prognosesenteret & Entelligens, 2011). Entelligens' energy audits of 100 dwellings do not give sufficient data for the info to be seen as reliable. The significant variation shows that the indoor temperature is connected to high uncertainty, and a small change in this variable will result in a significant impact on the heating demand.

The SFH03 example building operates with an indoor temperature of 20 °C, which is defined as the standard room temperature in the TABULA project. This is in the middle of the recommended values in NS3031:2014 and the barrier study report. As TABULA's standard values aim at reflecting the average values in all 16-member countries, it is highly realistic that this value does not correspond to the actual weighted average indoor temperature in Norway.

Infiltration/ventilation

Heat loss due to infiltration and ventilation in a building represents a significant heat loss source in the heat loss budget in Figure 17. The natural ventilation varies among the dwelling types and depends on air leakages in the building envelope. Prognosesenteret & Entelligens (2011) has found the natural ventilation, $n_{air,inf}$, and the corresponding air leakage rate, n_{50}, for single-family houses built between 1971 and 1980 to be respectively 0.4 [1/h] and 4 [1/h]. The value for natural ventilation is identical to the chosen value for the SFH03 example building the standard value for high infiltration in the TABULA model. However, the corresponding air leakage rate in the barrier study is almost 30 % lower than the air leakage rate found by SIMIEN's internal converter between natural ventilation and the air leakage rate. The corresponding air leakage rate in SIMIEN is the one used in the energy audit in this thesis. As shown in the sensitivity analysis, a change in the air leakage rate has a clear impact on the heating demand of the dwelling, and thus, the energy results from the barrier study yield a lower heating demand for SFH03 buildings.

5.2.2 The Dynamic Building Stock Model

The model developed by Sartori and Sandberg (2014b) is a result of decades of dynamic building stock development. Despite its weaknesses, it is a clear strength that the model has high accuracy concerning dwelling stock development in accordance to national statistics.

Dwelling stock development and stock composition

There are always short-term fluctuations in a dwelling stock over decades, something which makes the dwelling stock development non-linear. Sometimes these fluctuations are not dependent on the demolition activity, and hence, they are not possible predict and model. It is possible to correct in retrospect, but it is not implemented in an actual algorithm.

According to Bergsdal and Brattebø (2007) the lifetime of dwellings has a strong influence on the construction and demolition rate in a housing stock and is hence a critical parameter. Even though the lifetime for dwellings are taken from the most reliable source available, more research is needed in order to reduce the uncertainty of applying an unrealistic lifetime of dwellings.

One clear weakness to defining the total dwelling stock constructed during a specified time cohort is that it does not say anything about the dwelling stock composition throughout the time cohort. It only states how the stock looks like as a whole during that specific time span. This may create weaknesses in the model concerning the demolition shares and renovation shares defined throughout simulation.

Renovation

There do not exist sufficient statistical data when it comes to Norwegian renovation activity. This creates a significant uncertainty when modeling a dwelling stock with a renovation activity that reflects the actual renovation activity. The reason behind the lack of data is that most of the renovation activity is not specified, which makes it hard to estimate the quantity of for example façade refurbishments for a specific dwelling stock segment.

Renovation activity is dependent on more variables than the renovation cycle applied. Economy among households is also a critical parameter, creating fluctuations in the renovation activity. A wealthy economy in households will often result in more refurbishments, and vice versa, a worse economy in households will result in postponed refurbishments. The economy is not a variable that is accounted for in this model.

Renovation of dwellings may increase the user space, in addition to improving their energy characteristics. This is not accounted for in this analysis. In a future model implementation, this aspect may be integrated in the model implementation.

Another weakness regarding the implementation of the renovation function is that the model does not keep track of the number of times dwellings have been renovated. This might have been interesting to know when investigating the renovation activity of a dwelling stock segment when modeling for longer periods. However, this aspect is irrelevant when looking at energy results.

Energy use

The climate data has a significant impact on the energy use in the dwelling stock. Hence, if the climate data in the model are different from the actual outdoor climate in a particular period, this will give a discrepancy between the measured energy use and the modeled energy use. This has been the case for cold years, like 2010 (Meteorologisk institutt, 2014) , when there was a higher heating demand in the average dwelling than earlier. It is, however, possible to adjust the climate data from year to year in the model, so that it is possible to adjust climate data in retrospect. This is clearly a strength of the model, concerning modeling a similar energy use to the actual dwelling stock, including fluctuations in energy demand due to climate changes.

Population

The model has not accounted for a negative growth in population, which would add to a decreasing dwelling demand. A decreasing population is perhaps not a realistic scenario in Norway (SSB, 2014c), but the model is generalized and may as well be used for dwelling stocks with a decreasing population. Questions to answer in order to model residential stocks with a negative growth in population may be: Will the demolition increase? Should one assume a dwelling stock consisting of non-occupied dwellings for the ones moving out? Moreover, what will happen to the construction rate?

5.3 Implications of findings with respect to policy-making and future research

In coherence with the 2030 Framework, Norway has committed on reducing 40 %, or about 22 million tonnes CO_2 eq., of the national GHG emissions by 2030 compared to 1990 levels (Nrk, 2015; The European Commission). In order to fulfill the climate targets, different measures must be implemented in various sectors, including the building and housing sector. For the housing sector, we need to have an ambitious renovation strategy for the existing and ageing dwelling stock in order to reduce the future energy consumption. Since single-family houses represent almost 70 % of the heating demand in the Norwegian residential stock (see Table 2 in chapter 2), implementing energy refurbishment measures for these houses will have a significant impact on the total reduction potential in energy usage. The SFH03 stock segment accounts for about 13 % of all single-family houses. By introducing façade refurbishment measures for all ageing Norwegian single-family houses, this will contribute significantly to fulfilling future climate targets.

Long-term stock modeling of the SFH03 segment towards 2050 show that façade refurbishment contributes significantly in reducing the energy need for space hating and reducing operational carbon emissions. 93 % of the total SFH03 housing segment has refurbished the façade in 2050 when using a renovation cycle of 40 years. The predicted reduction in GHG emissions yields a 15 % reduction, or 0.05 million tonnes CO_2 eq. The relative reduction is significant, but the actual reduction contributes with only 0.2 % of the EU and national reduction target by 2030.

The baseline renovation strategy when long-term stock modeling is that dwellings renovated after 2010 will achieve a standard equal to the historically refurbished level. However, results from the investment analysis show that the insulation solution giving the lowest NPV value over 40 years of payback time was by far the TEK 10 solution for mineral wool insulation. This is the case even when the energy price is doubled and with an interest rate of 7 %. This result is surprising, as the TEK 10 standard for the outer walls requires an insulation thickness that is 25 % thicker than for a historically refurbished level. Unless climate policies for older dwellings change, it is more reasonable to assume that the most common refurbishment measure for the façade among SFH03 households in the future will be an upgrade to a historically refurbished level and not to TEK 10 standard.

SFH03 constitutes a small segment in the Norwegian residential stock. However, there is significant potential in energy saving and carbon reduction by adding supplementary insulation to the outer walls. By addressing this refurbishment measure to all single-family houses in need for façade replacement, this will have a positive impact on the total energy need and carbon emissions from the residential building stock. Further research is however needed in order to quantify the reduction potentials.

In addition, other refurbishment measures, like installing a heat pump, will reduce the delivered energy and operational carbon emissions even more. Air-to-air heat pumps have an average COP between 2.5 and 3, and will save up to 50 % of the total delivered energy for space heating compared to an electrical heating system (Stene, 2011). It may be interesting to look at a change in energy carriers or an increase in local energy sources (e.g. heat pump or solar power) for future research.

6. Conclusions

In this study, single-family houses constructed between 1971 and 1980 (SFH03) have been examined for different insulation solutions when adding supplementary insulation to the outer walls. Long-term modeling of the heating demand and carbon emissions towards the year 2050 for the SFH03 housing stock has given valuable insight of the reduction potential in energy usage and carbon emissions towards 2050 for façade refurbishments.

While it is clear that further research is needed, some preliminary conclusions may be drawn. Insulation solutions with mineral wool seems to be a better alternative than vacuum insulation. This is due to a better score than VIP materials concerning thermal characteristics, manufacturing cost and carbon emissions and energy use during manufacturing. In addition, there is a certain risk of maintaining the thermal characteristics of a VIP material concerning not perforating the materials and a natural decay that is higher than for mineral wool insulation.

In addition, the investment costs when applying vacuum insulation is significantly higher than for mineral wool insulation. The most economically viable insulation solution is fulfilling TEK 10 requirements. Applying vacuum insulation for the same renovation state results in a NPV value that is almost four times lower than the NPV value when using mineral wool insulation when using an interest rate of 5 % and a payback time of 40 years.

Sensitivity analysis in SIMIEN gives an indication that the model is robust to changes in the majority of the variables. However, the indoor temperature was the only variable that would give a larger change in percentage for the heating demand than the change of the room temperature. The weighted average value for the indoor temperature is associated with high uncertainty, as we do not have sufficient statistical data supporting the defined value.

Renovating the façade every 40 years results in refurbishing up to 93 % of the total SFH03 stock segment in 2050, achieving a minimization of energy usage and carbon emissions of 1/3 compared to 2010 levels. All other insulation solutions are more ambitious, and hence, gives an even higher reduction potential. However, a large amount of the reduction in energy consumption and carbon emissions is highly due to a significant amount of demolished SFH03 dwellings.

It seems more beneficial to implement a renovation cycle of 40 years instead of 30 years, despite achieving the same share of renovated dwellings in the SFH03 dwelling stock segment by following a 30-year renovation cycle. This is because the share of façade refurbished SFH03 buildings after 2010, called Rn3, is higher for the 40-year renovation cycle than for the 30-year renovation cycle, which results in a higher energy potential when the Rn3 insulation solution is more ambitious than the historical refurbishment requirements. Hence, the insulation solution influences the energy potential more than the actual renovation frequency. In addition, an “energy lock-in” effect occurs for the large amount of SFH03 dwellings that are forced to be in the same renovation state until the next façade refurbishment for the 30-year renovation cycle compared to the 40-year renovation cycle.

The dynamic building stock model utilized in this study yields realistic results, corresponding well with statistics concerning energy need in the dwelling stock and the dwelling stock development. This model seems therefore suitable for a more detailed long-term modeling of the future energy need for the Norwegian dwelling stock. However, in order to make the model reflect the dwelling stock and predict a realistic future energy demand and dwelling stock size, more data of the lifetime of dwellings and the timespan between refurbishments are needed.

7. Further work

In this master's thesis, some differences between the TABULA methodology and calculation methods used in NS3031:2014 and NS-EN 15725:2008 were observed. In future work, it could be interesting to do a more thorough and detailed study on the differences between the two energy audit models.

I have not investigated in detail the total energy savings and carbon emission reduction for the SFH03 stock segment when accounting for the upstream flows for the different insulation solutions. This may be of interest in further work for renovation of adding supplementary insulation to the outer walls.

The current material analysis does not include downstream energy and CO_2 flows. Performing an expanded analysis of waste treatment of mineral wool and VIP insulation should be included in further work.

In addition, there was only one stock segment investigated in the current study (SFH03). It would also be interesting to study the energy and GHG emission effects of refurbishments of the façade on single-family houses built in other time cohorts.

It may also be interesting to conduct a scenario analysis of the same dwelling stock segment (SFH03), including additional refurbishment measures, like changing the windows or installing a heat pump.

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Appendix 1: Thesis text

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2014-50

MASTER'S THESIS

for

Student Marianne Lie

Spring 2015

The effects of chosen energy refurbishment measures on direct and indirect energy demand, carbon emissions and energy costs for Norwegian detached houses built between 1956 and 1970

Effektene av valgte tiltak for energirehabilitering på direkte og indirekte energibehov, klimagassutslipp og energikostnader for norske eneboliger bygget mellom 1956 og 1970

Background and objective

The background of this master's 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 emissions situation of the standing residential building stock, and its dynamic changes over time due to stock growth, stock ageing, renovation opportunities, new building codes, building occupancy behaviour and the potentials for improvement in the system. The ongoing EPISCOPE project (using the TABULA method) examines such questions for the Norwegian residential building stock, and the student will contribute to the ongoing research by conducting an in-depth case study analysis of renovation opportunities of an important segment of the Norwegian residential building stock. The study of an assumed average building in the segment is combined with model results from a dynamic dwelling stock model to obtain results on dwelling stock level.

The objective of this master's thesis is to contribute to the understanding of long-term potential for reductions of energy demand in an important segment of the Norwegian dwelling stock. The student will study the different options for introduction of additional energy measures in single-family houses constructed in the period 1956-70 and their effects on material flows, energy demand, and greenhouse gas (GHG) emissions. This will be done for an assumed average building in the segment before the dynamic effects over time for the segment as a whole are analysed.

The following tasks are to be considered:

1. Carry out a literature review of the 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. Carry out an in-depth analysis of energy related renovation strategies for an average single-family house constructed in the period 1956-70 including their effects on material flows, life-cycle energy demand and GHG emissions.
4. Define relevant indicators and/or metrics for documenting the performance of the system.
5. Use the available segmented dynamic dwelling stock model to scale up the results to dwelling stock level (for this segment of the stock). Compare scenarios assuming different strategies regarding energy measures introduced when renovating as well as scenarios assuming different renovation intervals.
6. Report the results from the material, energy and GHG emission performance analysis of your system (including scenarios) and the particular importance of critical system variables, components or assumptions leading to these results.
7. Discuss the overall findings of your work, agreement with literature, strengths and weaknesses of your methods, and possible practical and/or methodological implications and recommendations of your work.

-- ” --

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

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

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

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

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

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

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

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

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
Olav Bolland
Department Head

H. Brattebø
Helge Brattebø
Academic Supervisor

Research Advisor: PhD-student Nina Holck Sandberg

Appendix 2: Equations and parameters

The following equations are calculations done in this project in order to carry out a thorough material analysis of the insulation materials examined and energy flows from the chosen building.

Equation 5 expresses the annual primary energy consumption to a system, dependent on the energy consumption of and energy export from the system. The current system does not export energy, and the second equation term is hence zero.

$$E_{p,r,i} = \sum_{j} (E_{j,r,i} f_{P,j}) N - \sum_{j} (E_{exp,j,r} f_{P,exp,j}) \qquad 5$$

$E_{p,r,i}$ Annual primary energy consumption in renovation state r for insulation type i[kWh]
$E_{,j,r,i}$ Energy delivered from energy carrier j, performing rehabilitation level r [kWh]
$E_{exp,j,r,i}$ Energy exported from energy carrier j, performing rehabilitation level r [kWh]
$f_{p,,j}$ Primary energy factor from delivered energy for energy carrier j [-]
$f_{exp,del,j}$ Primary energy factor from exported energy for energy carrier j [-]

Equation 6 defines the delivered energy to a system, where heat losses from the energy carriers are accounted for.

$$E_{r,i} = \sum_j y_j Q_{r,i} (1 + \eta_j) \qquad 6$$

$E_{r,i}$ Annual delivered energy in renovation state r for insulation type i [kWh]
$Q_{r,i}$ Annual energy need for heating in renovation state r for insulation type i [kWh]
y_j Share of energy supplied by energy carrier j []
η_j Energy efficiency for energy carrier j []
j Number of energy carriers in the heating system []

Equation 7 defines the annual operational carbon emissions from a building, dependent on the CO_2 coefficients from the respective energy carriers of the heating system.

$$C_{r,i} = \sum_j y_j E_{r,i} \mu_j \qquad 7$$

$C_{r,i}$ Annual carbon emissions from a building in operational state in renovation state r for insulation type r [kg CO_2 eq.]
μ_j CO_2 coefficient for energy carrier j [kg CO_2 eq. / kWh delivered energy]

Equation 8 defines thermal resistance ($R_{i,r}$) and measures how well a material can resist a heat flow.

$$R_{i,r} = \frac{d_{i,r}}{\lambda_i} \qquad 8$$

$R_{i,r}$	*Thermal resistance for insulation type i when renovating to rehabilitation level r [m^2K/W]*
$d_{i,r}$	*Thickness for insulation type i and renovation level r [m]*
λ_i	*conductivity of the material for insulation type i [mK/W]*

Equation 9 defines the overall heat transfer coefficient ($U_{i,r}$), describing how well a material conducts heat and is the inverse of the thermal resistance.

$$U_{i,r} = \frac{1}{R_{i,r}} \qquad 9$$

Equation 10 gives the quantity of thermal insulation needed ($M_{m,i,r}$) when renovating the outer walls of insulation type i.

$$M_{m,i,r} = \rho_i d_{i,r} S(1+k) \qquad 10$$

$M_{m,i,r}$	*Amount of insulation type i when renovating performing rehabilitation level r [kg/m^2 floor area]*
ρ_i	*Density of insulation type i [kg/m^3]*
$d_{i,r}$	*Thickness for insulation type i and renovation type r [m]*
S	*Factor for wall and floor area [m^2/m^2]*
k	*Percentage waste from purchased insulation material* $\left[\frac{\%}{100}\right]$

Equation 11 gives the amount of waste of insulation from new insulation on the construction site and original insulation being replaced ($M_{w,i,r}$).

$$M_{w,i,r} = \left(kM_{m,i,r} + lM_{o,i}\right) \qquad 11$$

$M_{w,i,r}$	*Amount of waste from insulation type i and renovation type r [kg/m^2 floor area]*
$M_{m,i,r,}$	*Amount of insulation type i when renovating with type r [kg/m^2 floor area]*
k	*Percentage waste from purchased insulation material* $\left[\frac{\%}{100}\right]$
l	*Percentage of original insulation being replaced from outer walls* $\left[\frac{\%}{100}\right]$
$M_{o,i,r}$	*Amount of original insulation in outer walls [kg/m^2 floor area]*

Equation 12 gives the energy consumption of insulation material manufactured and transported to the construction site ($Q_{i,r}$). This is referred to as the upstream energy flow.

$$Q_{i,r} = q_i R_{i,r} S \qquad 12$$

$Q_{i,r}$ *Energy consumption related to manufacturing and transport to construction site of insulation type i and renovation type r [kWh / m^2 floor area]*
$R_{i,r}$ *Thermal resistance of insulation type i when renovating to type r*
q_i *Energy consumption of manufacturing 1 m^2 insulation type i with a corresponding R-value of 1 W/ m^2K [kWh / 1R m^2 wall]*
S *Factor for wall and floor area [m^2/m^2]*

Equation 13 gives the amount of upstream CO_2 emissions, $E_{i,r}$ [kg CO_2/ m^2 floor area], from insulation material manufactured and transported to the construction site. This is referred to as the upstream CO_2 flow.

$$E_{i,r} = e_i R_{i,r} S \qquad 13$$

E_i *CO_2 emissions related to manufacturing and transport to construction site of insulation type i and renovation type r [kg CO_2/ m^2 floor area]*
e_i *CO_2 emissions of manufacturing of 1 m^2 insulation type i with a corresponding R-value 1 W/ m^2K [CO_2 / 1R m^2]*
S *Factor for wall and floor area [m^2/m^2]*

Equation 14 gives the manufacturing costs of insulation type i when renovating to energy state r ($C_{m,i,r}$).

$$C_{m,i,r} = \frac{\left(\frac{A_{wall}}{A_{ins,i,r}}\right) c_{m,i,r} x_d}{A_{ref}} \qquad 14$$

$C_{m,i,r}$ *Manufacturing costs of insulation type i when renovating to energy state r [NOK/ m^2 floor area]*
$c_{m,i,r}$ *Manufacturing costs of one package of insulation type i with a specified surface area for renovation level r [money unit/m^2 wall]*
x_d *conversion factor to NOK from specified money unit at date and time d []*
A_{ref} *Heated floor area [m^2]*
$A_{ins,i,r}$ *Surface area of specified insulation material package*

Equation 15 describes how to convert energy flows of a building into energy flows per m^2 floor area ($E_{x,ref}$).

$$E_{x,r,ref} = \frac{E_{x,r}}{A_{ref}} \qquad 15$$

$E_{x,r,ref}$ *Energy type x when performing renovation level r per* m^2 *floor area* $[kWh/m^2]$
$E_{x,r}$ *Energy type x when performing renovation level r [kWh]*
A_{ref} *Heated floor area* $[m^2]$

Equation 16 gives the net present value (NPV) of investment cost per heated floor area of refurbishing the façade to renovation level r and adding new insulation, relative to the energy saved over a time period of 40 years.

$$NPV = -\mathrm{I}_{\mathrm{r,i}} + \sum_{n=1}^{n=40} \frac{eQ_{r,i}}{(1+r)^n} \qquad 16$$

$I_{r,i}$	*Investment cost of manufacturing insulation material i, when renovating to renovation level r* $[NOK/m^2]$
e	*Average energy price for electricity [NOK/kWh]*
$Q_{r,i}$	*Annual energy saved when renovating to renovation level r with insulation material i per* m^2 *heated floor area* $[kWh/m^2]$
r	*real interest rate [-]*
n	*number of years since renovation of the outer walls [-]*

Equation 17 gives the conversion between the surcharge on the thermal bridges, ΔU_{tbr} [W/(m^2 envelope area K)], and the normalized thermal bridge values, tb [W/(m^2 floor K)].

$$\Delta U_{tbr} = \frac{(tb)A_{ref}}{A_{env}} \qquad 17$$

ΔU_{tbr}	*Surcharge on the thermal bridges [W/(*m^2 *envelope area K)]*
tb	*Normalized thermal bridge value [W/(*m^2 *floor areaK)]'*
$\ddot{A}_{env}$	*Surface area of the building envelope* $[m^2]$

Equation 18 gives the conversion between natural ventilation $n_{inf,air}$ [1/h] and n_{inf} [m^3/m^2h]:

$$n = \frac{n_{inf}V}{A_{ref}} \qquad 18$$

n	*Natural air change rate in a building, also known as the natural ventilation [1/h]*
n_{inf}	*Natural ventilation in cubic meters of air per* m^2 *heated floor area* $[m^3/m^2h]$
V	*Heated building volume*

Appendix 3: Important parameters

In the following table, all parameters used in the calculations in this master's thesis are summarized, with corresponding descriptions, values and units.

Parameter	Description	Value	Unit
A_{wall}	Surface area of the outer walls	186	m^2
A_{roof}	Surface area of the roof	87	m^2
A_{floor}	Surface area of the ground floor	87	m^2
A_{window}	Surface area of the windows and doors	23	m^2
A_{env}	Surface area of the building envelope	383	m^2
A_{ref}	Heated floor area	152	m^2
h	Floor height	2.4	m
V	Heated building volume	380	m^3
U_{wall}	Original state	0.40	W/m^{2}K
	Historically refurbished	0.29	W/m^{2}K
	TEK 10, min. wool	0.18	W/m^{2}K
	TEK 10, VIP	0.19	W/m^{2}K
	Passive house, min. wool	0.10	W/m^{2}K
	Passive house, VIP	0.12	W/m^{2}K
U_{roof}	U-value for the roof	0.21	W/m^{2}K
U_{floor}	U-value for the floor	0.23	W/m^{2}K
U_{window}	U-value for the windows and doors	2.6	W/m^{2}K
tb	Normalized thermal bridging factor	0.13	W/m^{2}K
n_{50}	Air leakage rate	5.7	1/h
n_{inf}	Natural ventilation	1	m^3/hm^2
$n_{inf,air}$	Natural ventilation	0.4	1/h
n_{use}	Air change rate by usage	0.4	1/h
ϑ	Indoor temperature	20	°C
α_{frame}	Window/frame ratio	0.3	-
η	Energy efficiency for wood	0.64	-
	Energy efficiency for electricity	1	-
f	Total primary energy factor for wood	1.09	-
	Total primary energy factor for electricity	1.28	-
μ	CO_2 coefficient for wood	0.261	[kg CO_2 eq./ kWh]
	CO_2 coefficient for electricity	0.05	[kg CO_2 eq./ kWh]
e	Average price for electricity	0.8367	NOK/kWh
r	Interest rate for baseline value	0.05	-
	Alternative interest rate	0.06	-
	Alternative interest rate	0.07	-
C	Manufacturing costs for min.wool, historically refurbished	66	NOK/m^2 wall
	Manufacturing cost for min.wool, TEK 10	76	NOK/m^2 wall
	Manufacturing cost for VIP, TEK 10	236	DKK/m^2 wall
	Manufacturing cost for min.wool, passive house	159	NOK/m^2 wall
	Manufacturing cost for VIP, passive house	372	DKK/m^2 wall

x	Conversion factor from DKK to NOK	1.12	NOK/DKK
R	Renovation cycle, lifetime of the façade. Baseline value	40	years
	Alternative renovation cycle	30	years
	Alternative renovation cycle	50	years