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Energy analysis of Trondheim's dwelling stock in order to identify and investigate differences between a national and local dwelling stock

Jan Sandstad Næss

Master of Energy and Environmental Engineering
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Supervisor: Helge Brattebø, EPT
Co-supervisor: Magnus Inderberg Vestrum, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

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MASTER THESIS

for

Student Jan Sandstad Næss

Spring 2017

Energy analysis of Trondheim's dwelling stock in order to identify and investigate differences between a national and local dwelling stock

Energianalyse av Trondheims boligmasse for å identifisere og undersøke forskjeller mellom den nasjonale og regionale boligmassen

Background and objective

The building stock represents a large share of the national energy demand, and is subject to ambitious policies on energy efficiency and shifts towards less carbon-intensive energy carriers. Current trends and recent analyses show that there is a large potential for energy improvements in the stock of existing buildings, and with an ageing building stock, such efforts become increasingly important. Parallel to the refurbishment process of aging buildings, new and better-performing buildings (TEK10, Passive house standard and NZEB standard) are added to the stock. Due to changing technologies and building codes in the past, the potential for improved energy intensity (kWh/m^2/year) and reduced greenhouse gas (GHG) emissions (kgCO_2-eq/m^2/year) vary between different segments of the dwelling stock. As a result, measures will vary significantly between the different building types and age cohorts. A consequence of this, due to different climatic conditions, is that the aggregated potential for improved energy efficiency and reduced greenhouse gas emissions will vary within a country, such as for different cities, between rural and urban building stocks, and between different type and age cohorts of the stock.

Previous studies have investigated both the characteristics and dynamics of the national dwelling stock of Norway and the energy characteristics of the stock in both a historic and prospective context. However, on a local scale, the dwelling stock and its energy characteristics might be of a different nature, and local policies, regulations and plans could mean that future energy consumption may differ a lot from the national case. Little research is done on how future development of local building stocks, and their respective energy characteristics, might differ from that of the national stock, and there is reason to believe that knowledge on differences and characteristics at the local scale would be of high value to local legislators, businesses and stakeholders.

The object of this MSc thesis is to carry out a systematic study of the energy characteristics of the dwelling stock in Trondheim, and perform an energy analysis of the stock with regards to scenarios of future development using a regionalized dynamic model developed in a previous MSc project. Further, the thesis should investigate how different refurbishment policies might affect the energy consumption of the stock, and identify the measures with the largest potential for reducing energy consumption in the stock. The focus of the thesis will be on gathering data on the past, current and likely future energy characteristics of the stock, including local policies and regulations regarding future energy requirements.

The following tasks are to be considered:

1) Carry out a literature study relevant to the work of the project, and gather necessary data for the project.
2) Refine the existing dynamic dwelling stock-energy model for use at the local scale, if needed.
3) Collect data on building stock and energy characteristics and other relevant region-specific conditions according to what is needed to run the dynamic dwelling stock-energy model for Trondheim.
4) Carry out dynamic modelling of the case of Trondheim, from 1960 until today and towards 2050, using scenarios that cover relevant policies, development patterns and technologies.
5) Discuss how your model results agree with empirical energy use and how the energy use of the local dwelling stock in Trondheim differs from that of the national stock. Discuss the reasons for this and possible implications, including how the dwelling stock in Trondheim could contribute to reach national emission and energy efficiency targets.
6) Discuss strengths and weaknesses of your work, and how your findings can be utilized I future projects investigating other environmental aspects of the dwelling stock.

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Within 14 days of receiving the written text on the master 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 analysed carefully.

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

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

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

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

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

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

Department of Energy and Process Engineering, 15. January 2017

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Professor Helge Brattebø
Academic Supervisor

Research advisor: PhD-student Magnus Inderberg Vestrum

Preface

The objective of this MSc thesis is to perform a systematic study of the energy characterisitcs of the dwelling stock of Trondheim and perform an energy analysis with regards to scenarios of future development using a regionalized dynamic model. The work has been carried out during the spring of 2016 at the Norwegian University of Science and Technology.

I would like to thank my supervisor Professor Helge Brattebø for his guidance during the work on this thesis. I have benefitted a lot from Helges superior knowledge of the industrial ecology field. Special thanks also to my co-supervisor Magnus Inderberg Vestrum that has been of great help. He has always had an open door and has been ready to help me out whenever I’ve encountered difficulties. Truly an everlasting resource. Lastly, I would like to thank Nina Sandberg for providing valuable insight into the model I have been working with. The speed at which Nina responds to questions by email has been remarkable and always with excellent well thought answers.

Abstract

The European Union has set ambitious targets for 2020 known as the 20/20/20 targets aiming to reduce greenhouse gas emissions by 20%, increase the share of renewables to 20% and improve energy efficiency by 20%. Buildings represents 40% of the final energy use in the EU and has a large potential for contributing to these targets by implementing energy efficiency measures. Refurbishment of aging buildings together with the implementation of better solutions for energy performance becomes important.

Often policy roadmaps use detailed information on energy and emission intensities, but lacks detailed information about the building stock itself. Renovation rates are often assumed to be easily increased by policy makers, but studies have shown that renovation rates are highly dependent on stock composition. As building stocks consists of different building types and age cohorts the potential for improved energy efficiency will vary due to changing technologies and building codes in the past. The energy characteristics and dynamics of the national dwelling stock of Norway has been investigated in previous studies. However, it is likely that the dwelling stock on a local scale could be of a different nature than the national average and that the local dwelling stock energy characteristics could differ from the national average. A regionalization of a dwelling stock model to develop specialized regionalized energy policies could prove to be of importance to local legislators, businesses and stakeholders.

This MSc thesis models the energy use from the Norwegian city of Trondheim's dwelling stock by using a regionalized segmented dynamic stock model. Statistical data has been gathered for the period of 1800 to present day, combined with population forecasts and implemented into the model. A detailed energy analysis has been run on Trondheim's dwelling stock based on stock composition and corresponding parameters for sub segments, archetypes and cohorts such as average heated floor area, energy intensities, energy mix and system efficiencies. Four possible future scenarios in addition to the business as usual scenario has been analyzed. The results suggest that the composition of Trondheim's dwelling stock differs from the national stock. The energy characteristics has also been shown to differ from the national average.

Trondheim's dwelling stock has been shown to have a larger share of Multi Family Houses than the national average. Additionally, the stock has a larger share of older dwellings. A future dwelling stock growth is expected. The energy analysis has shown that Trondheim's energy mix differs from the national average with a higher share of district heating. Historically, Trondheim's energy intensity has also been lower than the national average. Through the scenario analysis a roadmap giving possible future energy characteristics for Trondheim's dwelling stock has been created.

Baseline results suggests that even though the dwelling stock is expected to increase the delivered energy to the system is expected to experience only minor growth. However, the potential for future energy savings is large. In the most optimistic scenario a 37% decrease of delivered energy in 2050 compared to present day is expected. Somewhat surprisingly it has been shown that the potential for energy efficiency measures through advanced and more frequent renovation is limited. This is due to that much of the possible gains will be reached anyway before 2050 through natural standard renovation. However, an extensive policy of local energy use by using HPs and PVs has proven to be very effective and represents the largest opportunity for energy savings towards 2050. Moreover, it has been shown that there is a large potential to shift the current energy mix in the city to a larger share of district

heating in 2050. This could represent an opportunity to free surplus electricity that can then be used to replace more carbon intensive energy carriers in other sectors. For instance, by powering a future electrical vehicle park with electricity.

It has been shown that it will also be important in Trondheim as found for the whole country by Sandberg et al. (2017) to make efforts to limit the expected rebound effect. As the theoretical estimated energy need intensity decrease in the stock a change in user behavior is expected to counteract the improved energy efficiency through a higher energy use. This will limit the potential for energy savings in the stock and policies should be created to minimize this change in user behavior.

The findings suggest that regionalized dwelling stock models will indeed be of great use for local policy makers. It has given much needed insight into Trondheim's dwelling stock composition. The model's ability to assess the stock's energy mix on a per type, cohort and archetype level has proven to be of key use when assessing the potential for district heating in Trondheim. Through a scenario based energy analysis of a segmented dynamic dwelling stock model different possible energy policies can be compared and tested against each other on a long-term scale.

Sammendrag

Den Europeiske Union har satt ambisiøse mål for 2020 kjent som 20/20/20 målene som sikter mot en reduksjon av klimagassutslipp på 20%, en økning i andelen fornybar energi til 20% og en 20% økning i energieffektivitet. Bygninger representerer 40% av endelig energibruk i EU og sektoren har et stort potensiale for å bidra til å nå disse målene gjennom å implementere tiltak for å øke energieffektivitet i bygg.

Politiske veikart bruker ofte detaljert informasjon om energi og utslippsintensiteter, men mangler detaljert informasjon om hvordan bygningsmassen faktisk ser ut. Renovasjonsrater er ofte antatt å være lette å forandre av beslutningstakere, men studier har vist at renovasjonsrater er svært avhengige av bygningsmassens komposisjon. Bygningsmasser består av ulike bygninger tilhørende forskjellige bygningstyper og alderskohorter og potensialet for å forbedre energieffektiviteten vil variere over tid med teknologiske forandringer og byggeforskrifter. I Norge har dynamikken i den nasjonale boligmassen samt boligmassens energikarakteristikk blitt undersøkt i tidligere studier. Derimot blir det sett på som sannsynlig at boligmasser på det regionale plan kan være av en vidt forskjellig natur enn landsgjennomsnittet. Lokale bygningsmassers energikarakteristikk kan også være forskjellige fra landsgjennomsnittet. En regionalisering av en boligmassemodell kan vise seg å være svært nyttig for å utvikle spesialisert energipolitikk på det regionale plan og bli viktig for lokale lovgivere, bedrifter og aktører.

Denne masteroppgaven har modellert energibruken fra boligmassen for den norske byen Trondheim ved å bruke en regionalisert segmentert og dynamisk bygningsmassemodell. Statistiske data har blitt samlet inn for perioden 1800 til nå, blitt kombinert med populasjonsframskrivinger og implementert i modellen. En detaljert energianalyse har blitt kjørt på Trondheims boligmasse basert på boligmassens komposisjon og med tilsvarende parametere for undersegmenter, arketyper og kohorter som gjennomsnittlig oppvarmet gulvareal, energiintensiteter, energimiks og systemeffektiviteter. Fire mulige framtidsscenarioer har blitt analysert i tillegg til et «business as usual» scenario. Resultatene tyder på at komposisjonen av Trondheims boligmasse er forskjellig fra det nasjonale snittet. Energikarakteristikken har også blitt vist å være forskjellig.

Trondheims boligmasse har en større andel leiligheter enn nasjonalsnittet og i tillegg er det en større andel eldre boliger. Mot 2050 er det forventet en vesentlig vekst i antall boliger. Energianalyser har vist at det er en mye høyere andel fjernvarme i Trondheim enn i energimiksen for hele landet. Historisk har Trondheim hatt en lavere energiintensitet enn landsgjennomsnittet. Gjennom scenarioanalyser har et veikart av mulige fremtidige energikarakteristikker for Trondheims boligmasse blitt laget.

Baseline resultatene tyder på at selv om boligmassen er forventet å vokse så er det bare forventet en svært liten vekst i fremtidig levert energi til systemet. Potensialet for fremtidige energibesparelser er derimot stort. I det mest optimistiske framtidsscenarioet er det forventet en nedgang på 37% i totalt levert energi i 2050 fra i dag til boligmassen. Noe overraskende har det blitt vist at potensialet for energieffektivitetstiltak gjennom avansert og hyppigere renovering er begrenset mot 2050. Dette er på grunn av at en stor del av den potensielle gevinsten vil nås uansett før 2050 gjennom naturlig standard renovasjon. Derimot vil et tiltak for omfattende bruk av solceller og varmepumper ha svært stort potensiale for å reduser levert energi til systemet frem mot 2050. Videre har det blitt vist at det er et stort potensial for å

gjennomføre et skifte i energimiksen til en større andel fjernvarme med spesifikke tiltak for å promotere dette. Dette kan frigjøre elektrisk energi fra boligsektoren som kan brukes til å erstatte mer karbonintensive energibærere i andre sektorer. For eksempel ved å tilføre energi til en fremtidig elektrisk bilpark.

Det har blitt vist at det blir viktig også i Trondheim som for hele landet slik det ble funnet av Sandberg et al. (2017) å begrense «rebound effekten». Når teoretisk estimert energiintensitet synker i boligmassen er det forventet at en forandring i brukeratferd vil føre til høyere energibruk og motvirke den forbedrede energiintensiteten. Dette vil begrense muligheten for energibesparelser i boligmassen og tiltak bør implementeres for å minimalisere denne forventede forandringen i brukeratferd.

Funnene i denne masteroppgaven tyder på at regionaliserte boligmassemodeller vil bli svært nyttige for lokale beslutningstakere. Modellen har gitt god innsikt i Trondheims boligmasse og dens komposisjon. Modellens evne til å modellere energimiks etter boligtype, kohort og arketype har vist seg å være en nøkkel for å analysere potensialet for fjernvarme i Trondheim. Gjennom en scenariobasert energianalyse av en segmentert dynamisk boligmassemodell kan fremtidige mulige energitiltak bli sammenlignet og testet mot hverandre i et langtidsperspektiv.

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1. Introduction

1.1 Background/High level overview

The twenty-first annual United Nations conference on climate change was held in Paris in December 2015. The Paris Agreement includes a legally binding target to limit global warming to 2◦C above pre-industrial levels (Vandyck et al., 2016). It represents an important step in international climate change negotiations. To achieve this target, the global greenhouse gas (GHG) emissions must be reduced. In 2010 the buildings sector accounted for 19 % of the GHG emissions (Edenhofer et al., 2014). At the same time, it accounted for 32 % of the global final energy use. CO2 emissions from buildings are projected to increase further towards 2050.

The European Union (EU) has committed to a roadmap aiming for 80-95 % reduction in GHG emissions by 2050 with the goal of moving towards a low-carbon economy (European Commission, 2011). An energy savings target of 20% by 2020 has been set by the EU. The building sector represents 40% of the total final energy consumption and can make a crucial contribution to these targets (Buildings Performance Institute Europe, 2011). In order to reduce emissions from the building sector measures like improving energy efficiency needs to be considered.

According to the European Commission (2011) the largest energy savings potential in the EU lies in buildings. Since the early 1990s individual member states has adopted a wide range of measures to actively promote improved energy performance in buildings. In 2002 the Directive on Energy Performance of Buildings was adopted and then again recast in 2010 to make the goals even more ambitious and reinforce the implementation. On the national level the approaches to monitor the building stock has evolved separately. To develop a European pathway and roadmaps to more energy efficient buildings better information and data is needed. The lack of data in the building sector is a major obstacle to strong policy making at EU level (Buildings Performance Institute Europe, 2011). To have a good basis for policy making a detailed and correct picture of the building stock must be created.

The residential building stock represents 75% of the total floor space in the total EU stock (Buildings Performance Institute Europe, 2011). The residential stock can again be separated into different types of single family houses (detached, semi-detached and terraced houses) and apartment blocks. The Buildings Performance Institute Europe (BPIE) found in 2011 that 64% of the residential floor space was associated with single family houses (detached dwellings) and 36% with apartments (compact dwellings). This split between the two residential property types varies a lot on the national level between countries. For instance, according to the BPIE (2011) Estonia, Latvia and Spain have the highest share of apartments, while Greece, Ireland, Norway and UK have the smallest. Different dwelling types have different energy intensities and through knowledge of the building stock's composition can measures to decrease its need for delivered energy be identified.

Norway has set goals to become a low emitting society by 2050 and is aiming for a 40% reduction in carbon emissions by 2030 compared to 1990 levels (Miljødirektoratet, 2017). On a more regional level the Norwegian municipality of Trondheim has set local goals of reducing the GHG emissions by a at least 25% by 2020 compared to 1991 levels. Accordingly, the 2050 target is a reduction of 70-90% of 1991 levels (Trondheim Kommune, 2010) . The 2020 targets are planned to be reached through emission reductions locally in Trondheim alone and differs from the national climate policies where GHG emission targets are planned reached through a combination of national efforts including the binding of CO_2 in forests and measures abroad including buying carbon offsets. The 2020 targets presented by Trondheim Kommune (2010) means that the yearly emissions in 2020 should not exceed a total of 372 000 CO_2 equivalents or 1.9 tons CO_2 equivalents per capita.

Trondheim's dwelling stock has the potential of contributing to reaching these targets. Even though Norway has a large hydropower resource that dominates the energy mix a decrease in delivered energy from electricity to dwellings could allow more electricity to be used in other more carbon emission heavy sectors. A reduction in CO_2 emissions related to the dwelling stock might possibly be achieved by lowering the stocks demand for delivered energy through energy efficiency measures and renovation or by more extensive use of local energy sources like photovoltaics (PV) and heat pumps (HP).

1.2 Problem definition

To improve the knowledge of how a regional dwelling stock's energy use might differ from a national level a case study will be done for the Norwegian city of Trondheim. The following research questions has been developed as a basis for the work:

- What will be the energy characteristics of the dwelling stock in Trondheim in 2050 compared to today and previous years?
- How does the energy use from the Trondheim dwelling stock differ from the national one?
- How could the Trondheim dwelling stock contribute to reaching national emission and energy efficiency targets?

2. Literature study

To investigate what earlier research has been done on modelling of dwelling stocks and energy use from dwelling stocks a literature study has been done. First available energy technologies and energy efficiency measures in buildings are studied. Then dwelling stock and dwelling energy use modelling is considered. Lastly, the chosen case of Trondheim is studied.

2.1 Technologies and energy efficiency measures

To reduce the energy use and GHG emissions from buildings measures can either be done by increasing the energy efficiency of the building or by converting the energy mix (Norges vassdrags- og energidirektorat, 2010).

Energy efficiency measures decrease the energy need of buildings. This can be done by improving the energy intensity [kWh/m^2/year] through renovating the current building stock and by making sure new construction has a high-energy performance. Some energy efficiency measures include better isolation, stopping air leaks, energy monitoring, better energy management, using the best available technologies and choosing low-energy solutions (Norges vassdrags- og energidirektorat, 2010).

Converting the energy mix in the system can be done by removing the use of fossil fuels to heating and hot water in buildings (Norges vassdrags- og energidirektorat, 2010). For instance, by removing an oil boiler and connecting a waterborne heating system to a district heating network.

2.1.1 District heating

Approximately 6000 district heating systems can be found in Europe today with a total distribution pipe length of about 200 000 km. It covers about 13% of the current European heat market for buildings (Connolly et al., 2014). Local renewable resources can be utilized through district heating and heat that is wasted in parts of the existing energy system can be recycled. District heating is used as a supply for heat in different buildings in cities, primarily multi-family houses and service premises. The heat is used through a central waterborne heating system for the whole building for preparation of domestic hot water (dhw) and space heating. The system can use various energy sources and become an important actor for waste management systems, forestry, power production and efficient energy use (Gebremedhin, 2012). Much waste is landfilled and by using the waste as fuel to extract energy landfilling can be reduced.

District heating plants require large initial investment costs, but have low operation costs once constructed. A long term perspective on profitability is needed and the cash flow should be expected to be negative during the first few years after the establishment of a new district heating system (Gebremedhin, 2012). Policy support might be needed to create the development of new district heating infrastructure. Heavy investments such as a combined heat and power plant (CHP) requires a certain size to be profitable and might need a large district heating system to be sustainable.

In Norway electricity is widely used for heating of buildings as shown in Figure 1. District heating is much more extensively used for heating and hot water in other Nordic countries. A switch from electric heating to another source of energy would reduce the electricity consumption from buildings, but would also allow for the electricity to be used for other purposes (Gebremedhin, 2012). If the district heating plant that a customer switch to is a CHP plant this would again allow for greater production of electricity at the CHP plant and thus creating a positive feedback.

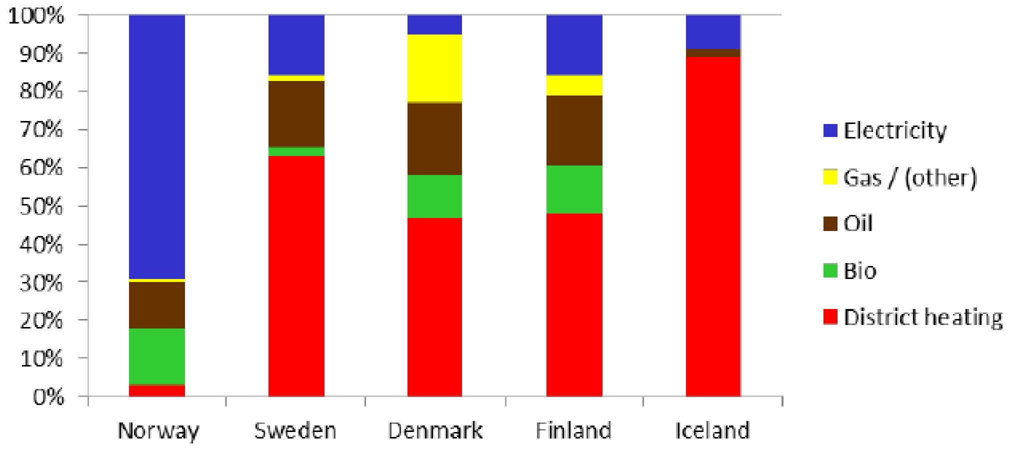


Figure 1: Share of energy carriers in the Nordic heat market (Gebremedhin, 2012).

Carbon emissions from district heating will depend on the energy mix in the combustion fuel. A life cycle impact assessment of district heating was done by Bartolozzi et al. (2017) which showed a global warming potential (GWP) in the range of 0.142-0.263 kg CO_2-eq/kWh depending on the fuel with the best result obtained assuming a fuel mix of 75% biomass from local supplied short rotation forestry cultivation of poplar and the remaining 25% from thinning of forest wood. Another study performed in Norway on the waste to energy district heating plant of Heimdal in Trondheim found a GWP in the range of 90-220 kg CO_2-eq/kWh (Lausselet et al., 2016). Also in this study the results were highly dependent on the fuel mix. Direct emission occurring at the plant was a key contributor and CO_2 emissions ranged from 240-450g per kg waste.

2.1.2 Photovoltaics (PV)

PV use has rapidly increased in recent years and are used to convert solar energy to electrical DC energy (Al-Waeli et al., 2017). PVs use semiconducting materials to generate electricity from light. The smallest unit is called a solar cell and several solar cells are put together to a solar panel. PV installations can be mounted to the roof, wall or the ground and generates no GHG emissions or pollution after installation. Generated electricity depends on

PV systems still face significant challenges as generated energy from PV depends on many different factors such as location solar irradiation and meteorological variables. Fluctuations in the generated energy output creates problems for the energy system as it is difficult to store generated electricity over time. This can potentially be balanced by an energy storage system like batteries (Nyholm et al., 2016) or for instance on a broader scale a pumped-storage hydropower system (Gullberg, 2013).

Electricity generation from PVs depends on solar irradiation. Laleman et al. (2011) performed an analysis of life-cycle carbon emissions from photovoltaics used in residential systems located in regions with a solar irradiation of 900-1000 kWh/m^2/year which is applicable to Norway. Assuming a PV lifetime of 30 years the corresponding GWP potential was found to be 0.08 kg CO_2-eq/kWh (Laleman et al., 2011). A further literature review of calculated global warming potential done by various researchers was also done by Laleman et al. (2011) and is shown in Figure 2. The life-cycle global warming potential of photovoltaics is higher than for wind and nuclear power. Still the potential for a reduction of greenhouse gases through replacing fossil fuels like gas and coal is large.

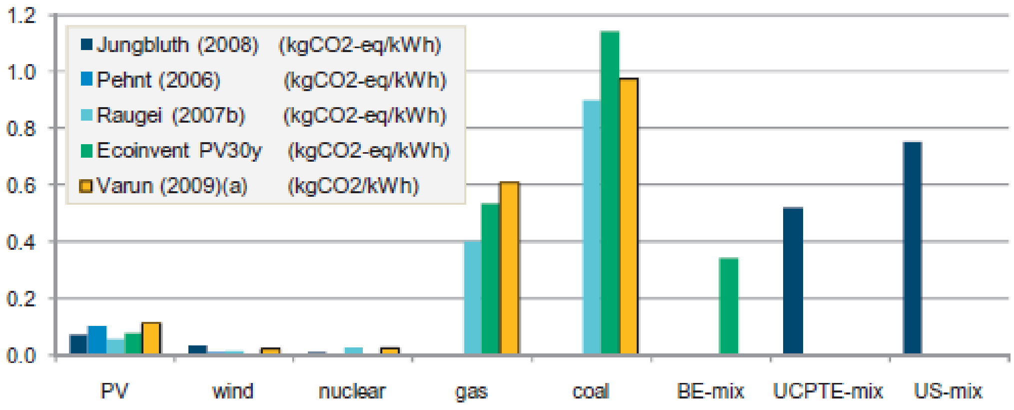


Figure 2:Global warming potential [kg CO_2-eq/kWh] for different sources of electricity generation, Belgium mix (BE-mix), European mix (UCPTE-mix) and USA mix (US-mix) according to various authors (Laleman et al., 2011).

2.1.3 Heat pump (HP)

HPs runs on electricity and use heat from the surroundings to heat buildings. Common type of HPs in Norway are air to air, air to water and water to water HPs (Norges vassdrags- og energidirektorat, 2010). The most common type of HPs in Norway is air to air and is mainly used by dwellings. This type utilize heat from the ambient air and delivers heat to the building through a fan. The COP of an air to air HP is normally about 2-3 and decrease with decreasing ambient temperature. The second type of air to water HPs utilize heat from ambient air and delivers heat to the building through a waterborne distribution system with a COP of about 2.5-3.5. Lastly, water to water type HPs utilize heat from surrounding lake, sea or ground and has a COP of 3-4 (Norges vassdrags- og energidirektorat, 2010).

2.1.4 Other technologies

The other main technologies that are used for space heating and dhw in Norwegian dwellings are biofuels, heating oil and grid electricity. Norway is a special case internationally as most of the energy mix in delivered energy to buildings is electricity from grid generated by hydropower as seen in Figure 1. The Norwegian energy policy is to phase out the use of oil boilers and fossil fuels in households and base loads towards 2020 (Ministry of The Environment, 2012).

According to Norges vassdrags- og energidirektorat (2010) the biofuels carbon intensities for energy delivered to dwellings in Norway from firewood is 0.024 kg CO_2-eq/kWh and from wooden pellets 0.022 CO_2-eq/kWh. Carbon intensity from heating oil is given as 0.265 kg CO_2-eq/kWh, coal 0.425 kg CO_2-eq/kWh and gas 0.227 kg CO_2-eq/kWh. The numbers for oil, coal and gas seems somewhat low compared to the presented numbers in Figure 2. This could be due to that they are direct emission intensities from the combustion of the fuel to produce heat and not life cycle emission intensities for electricity generation.

The life cycle carbon intensity for the electricity consumption mix was given by Hertwich & Roux (2011) as 0.05 kg CO_2-eq/kWh for Norway, 0.21 kg CO_2-eq/kWh for the Nordic mix and 0.56 kg CO_2-eq/kWh for the European mix. Norway has a very clean electricity mix due to its large share of hydropower.

2.2 Modelling of dwelling stocks

2.2.1 International modelling

Müller (2006) developed a dynamic stock model to analyze the Dutch dwelling stock. This model was based on dynamic MFA principles and used the underlying drivers in the dwelling stock system such as population, floor area per capita, buildings lifetime and material intensity per unit floor area. Demolition activity estimates used a lifetime probability function and historical construction activity, while the construction activity was calculated through mass balancing principles.

Bergsdal et al. (2007) modified the model created by Müller and applied it to the Norwegian dwelling stock. Sartori et al. (2009) developed Sartori et al. (2009) developed it further to model renovation flows.

A similar dynamic model was used by Hu et al. (2010) on the Chinese dwelling stock. As dwelling stocks differ greatly between rural and urban housing stocks in developing countries the idea was to identify long term dynamics of floor area in both types. It was found that lifetime distribution of the building stock was a factor that played a large role in determining future construction and demolition levels. It was expected that a decline in construction activity would happen in urban housing systems. In rural housing systems construction demand had already been decreasing the last decade, and future demand will depend on urbanization pace.

Recently Sandberg et al. (2016) used the developed dynamic building stock model to perform a study on the building stock of 11 European countries. The model produced results that fit well with statistical data for all countries. It was shown that renovation rates were in the range of 0.6-1.6%, which is far from the 3% target. Therefore, it is very important to make sure that energy efficiency measures are included when dwellings in less developed regions are renovated.

According to Sartori et al. (2016) the dynamic dwelling stock model gives a deep understanding of different dynamics that drives developments in dwelling stocks. Future projections of stocks can be obtained. As deep renovations are considered to go in 40 year cycles Sartori et al. (2016) shows that until 2050 there will on average only be one chance of renovating a post WWII dwelling when assuming 40 years' renovation cycles. This highlights again the importance of making sure that energy efficiency measures are implemented when a building goes through a deep renovation.

2.2.2 National modelling of the Norwegian dwelling stock

According to Brattebø et al. (2009) there were 3.84 million buildings in Norway out of which 1.45 million were residential buildings in 2009. This gives a number of 0.30 residential buildings per capita in the country, and the building stock has quadrupled since 1950. This increase can be explained by major socio-economic and demographic changes. A modest building boom happened in the early 1950s and a large boom in the mid-1980s. A decrease in the amount of construction was seen around 1990 while the amount of construction has increased again towards 2009. The historical development of the Norwegian construction activity in the period of 1945-2007 was modelled as shown in Figure 3.

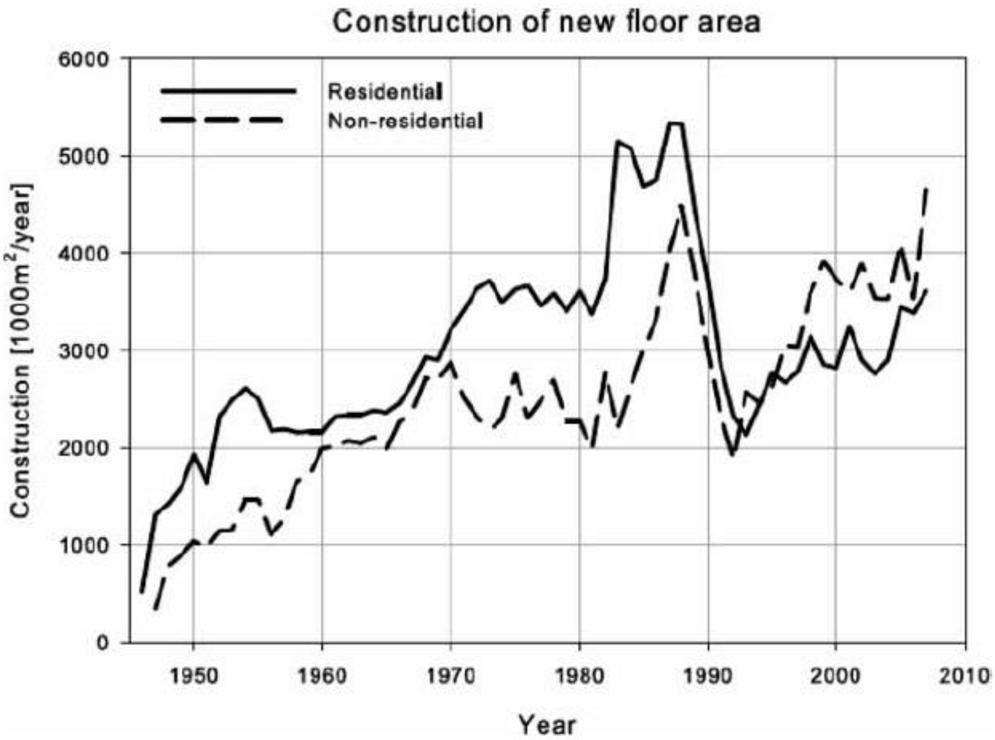


Figure 3: Construction activity in the Norwegian building stock modelled for the time period 1945-2007 (Brattebø et al., 2009).

The increase in GHG emissions due to society's growing energy demand calls for long term technological and cultural changes. The building sector stands for a large share of the global emissions and will have to take its fair share of emission reductions (Sandberg et al., 2011). The building stocks aggregated energy consumption depends on the energy efficiency of buildings and the size and composition of the stock. It is therefore important to have good knowledge about the composition of the building stock. According to Sartori et al. (2009) the gross floor area in the residential building stock increased from about 250 million m^2 in 1982 to about 320 million m^2 in 2005. At the same time the national total energy consumption in residential buildings increased from 38 to 44 TWh per year while the energy intensity has decreased from 214kWh/m^2 in 1983 to 204 kWh/m^2 in 2005. This decrease in energy intensity is due to a larger share of new dwellings being apartments in compact houses instead of detached houses with higher energy consumption.

One difference with the Norwegian dwelling stock compared to most other countries is that electricity is widespread used for heating as electricity prices are low since it is almost exclusively produced from hydropower (Sandberg et al., 2011). As hydropower is a renewable energy source an electricity mix with a lot of hydropower represents a smaller amount of GHG emissions than for instance the European electricity mix that includes shares of fossil fuels in the production phase.

A case study was done on the Norwegian dwelling stock by Sandberg et al. (2014b) by segmenting the stock into two dwelling types and five construction periods. Renovation cycles of 20, 30 and 40 years was used. The 20-year renovation cycle represents replacement of appliances (boilers etc.), the 30-year cycle replacement of building components (windows, roofs, etc.) and the 40-year cycle represents deep renovations of facades. The study done by

Sandberg et al. (2014b) is based on work previously done as explained in section 2.2.1, but models the dwelling stock dynamics in number of dwellings instead of floor area to remove the parameter of average floor are per dwelling which has been considered to be very uncertain. The model use input data that has been thoroughly revised and describes the dwelling stock segmented in types and construction periods. An outline of the model is provided in Figure 4.

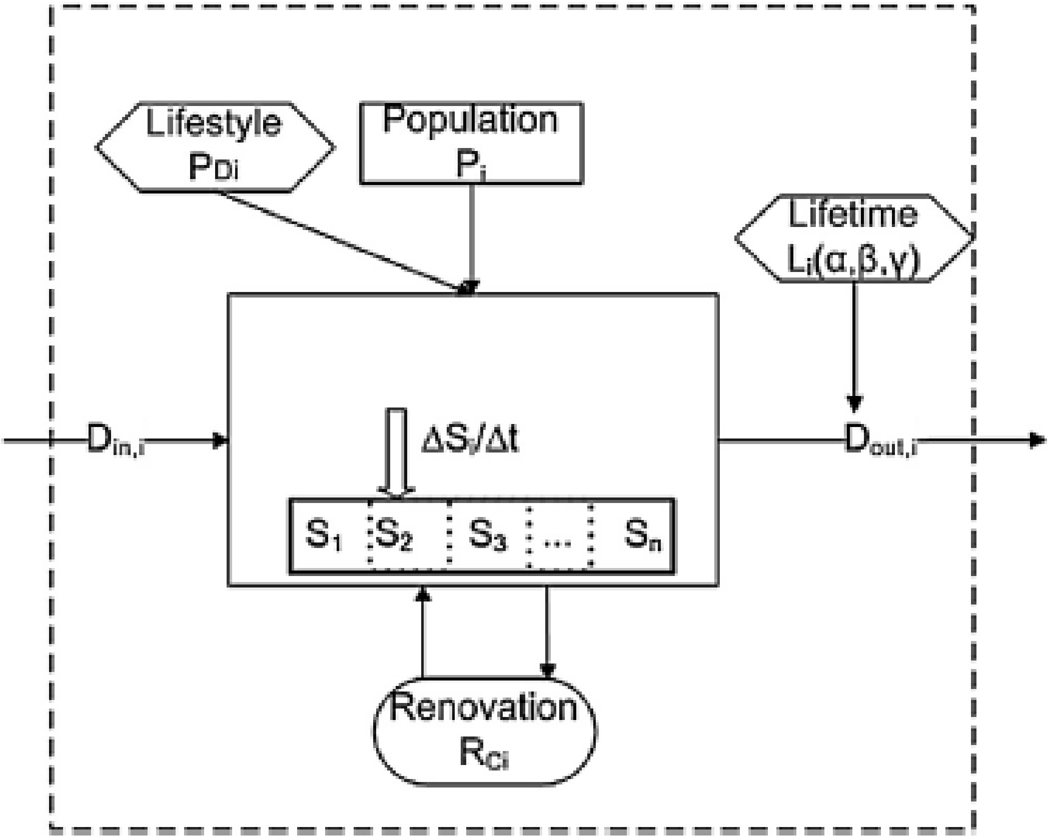


Figure 4: Conceptual outline of the segmented model with drivers and flows illustrated for segment i (Sandberg et al., 2014b).

The model outlined in Figure 4 describes long term dynamic development of dwelling stock demand and construction, renovation and demolition activities in the system. It is applied for both the total stock and for segments of the stock defined by dwelling type and construction period. Input parameters are needed as full time series for each dwelling type as well as the total stock. The model core is the demand for dwellings given as total dwelling stock S, population P and lifestyle quantified as persons per dwelling P_D. The underlying methodology and mathematics for the model is further described by Sandberg, (2014a) and Sartori et al. (2016).

In the case study for Norway a time horizon from 1800 to 2050 was used (Sandberg et al., 2014). Two segments of the dwelling stock were used, detached and compact houses. Similar policy measures were assumed to fit dwellings of each type. The detached houses segment corresponds to single family houses, farmhouses, semi-detached houses, terrace houses and other residential houses with less than three stories. Compact houses refer to apartment blocks and other residential houses with three or more stories. At the same time the five segmented cohorts used in the model are split into dwellings constructed before 1945 in cohort 1-2, post war construction boom in cohort 3, constructed buildings from the recent decades in cohort 4 and future expected constructed dwellings in cohort 5. This gives 10 archetypes representing the building stock when combining cohorts and dwelling types.

The population input data used in the national model by Sandberg et. al (2014b) is based on statistics available for every 10 years before 1980 and then yearly data to present and the medium scenario created by Statistics Norway's future population projections. To smoothen out the curves and remove short term fluctuations from the results linear interpolation is performed. The population data and smoothed curves for the given time series are shown in Figure 5. Population data is then split into the two dwelling types according to their shares.

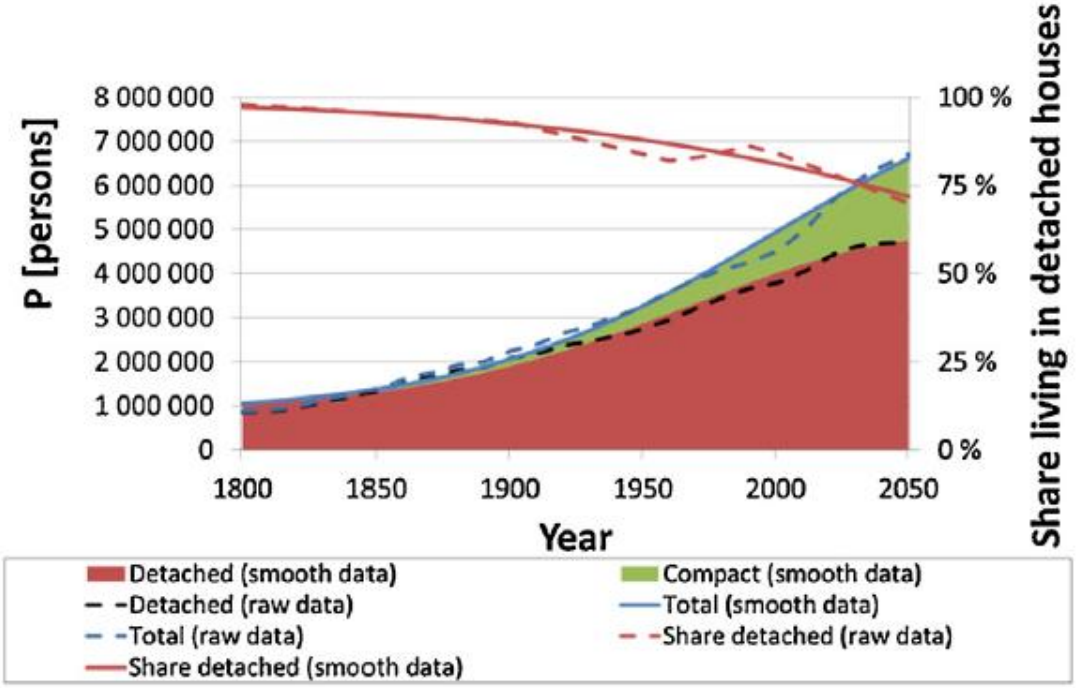


Figure 5: Development in total population and in persons living in each of the two dwelling types (Sandberg et al., 2014).

The national average number of persons per dwellings has decreased from 5.4 in 1800 to 2.2 in 2011. It is assumed a minor further decrease towards 2.1 persons per dwelling in 2050. After 1960 the number of persons per dwelling can be derived directly from census data. Sandberg et al. (2014b) assumes that P_D in 1800 is equal for the two types, but that the P_D in detached houses is higher than for compact houses in 1900. In 2050 the P_D is assumed to be 1.55 in compact houses. P_D is calculated such that the average equal the total stock average in compact houses in 1900 and detached houses in 2050. In the same way, as with the population data the P_D numbers are interpolated to smoothen out the curves and remove short term fluctuations. The result produced by Sandberg et al. (2014b) is shown in Figure 6.

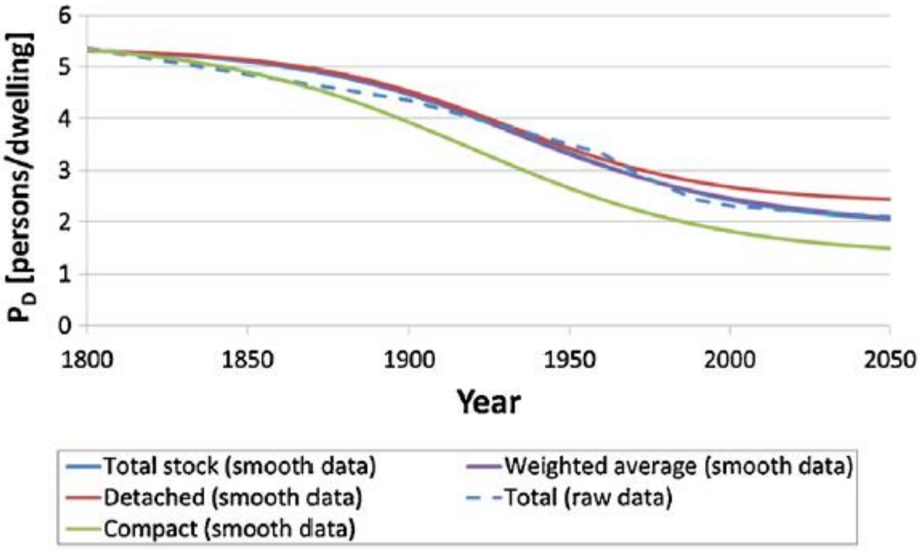


Figure 6: Development in persons per dwellings at national level (Sandberg et al., 2014).

Assumed building lifetime is important for the model results. For the model it has been assumed an average dwelling lifetime of 125 years that corresponds to an estimation done by Bohne et al. (2006). There is high uncertainty related to the lifetime distribution (Sartori et al., 2016). A Weibull probability distribution is used to calculate the demolition rate of buildings. The Weibull distribution is considered to give a better picture of the actual demolition activity than the often-used normal distribution. It is assumed that the probability of a demolition happening the first 40 years of a buildings lifetime is 0. The long tail of the Weibull distribution represents the heritage buildings that are preserved and never demolished. The three previously mentioned renovation cycles are modelled with a normal probability distribution with the average renovation time of respectively 20, 30 and 40 years. Because of the Weibull lifetime distribution, a dampening effect on the renovation profiles can be observed as shown by Sandberg et al. (2014b).

The results of the case study performed by Sandberg et al. (2014b) showed that construction activity is expected to increase towards 2050 on the national level in Norway and the long term need for new construction is going to be about 40 000 dwellings per year. Demolition activity is also expected to increase as the buildings that were constructed in the construction boom after the war will start reaching their end of life. Replacement of existing buildings will be the most important driver for new construction activity towards the end of the current century.

Renovation activity is expected to increase with more than 30% towards 2050. Activities connected with the 20-year renovation cycle is expected to increase to about three times the number of dwellings constructed by 2050 (Sandberg et al., 2014b). Dwellings exposed to the 30-year renovation cycle is expected to reach about 3% of the total stock in 2050 and which is around 1.5 times the total construction activity. For the 40-year cycle the renovation activity is expected to approximately equal the construction activity in 2050 As the EU has policy targets of reaching 3% renovation rates of deep facades by 2030 this corresponds to a renovation cycle of less than 30 years and seems very ambitious to accomplish at the Norwegian national level. The Norwegian dwelling stock consists of a higher share of detached houses than compact houses, and therefore the renovation activity is dominated by detached houses. Towards 2050 Sandberg et al. (2014b) expects the share of compact houses being renovated to increase.

2.3 Historical modelling of energy use from dwelling stocks

Robust building stock models are important when it comes to informing decision makers about effectiveness of different policies or combinations of policies when it comes realizing current goals, defining realistic goals, prioritizing climate change mitigation strategies and avoiding misinformation, fragmented actions and policies that lead to weaker results in the long run (European Commission, 2014). By using models that analyze the development of building stock characteristics energy demand from building stocks can be calculated. The energy demand from a building stock is calculated by multiplying the stock size with the average energy intensity per square meter (Sandberg et al., 2016b).

Various attempts have previously been done to model energy use from dwelling stocks. Vásquez et al. (2016) splits existing models into the three main model types accounting, quasi-stationary and dynamic. Dynamic models can further be divided into input- or activity-driven models and stock driven models. Accounting models quantifies stock size and composition together with its material or energy flows. Quasi-stationary models typically study the building stock for a single year, while dynamic models analyze a longer time frame and multiple years. Activity driven models use construction and demolition rates from historic trends as drivers. Stock-driven models rely on time changing factors like population and building type and size preferences, and use the service demand/provision concept (Müller, 2006). They also use the building's lifetime to explain and estimate construction and demolition activities. This also means that it is needed to model over a longer timespan due to the long building lifetime. Renovation impact can be captured by the use of renovation rates or renovation cycles (Vásquez et al., 2016). A further literature study of existing models and studies for energy use in building stocks can be found in the work done by Vásquez et al. (2016).

2.3.1 Norwegian national case study

The segmented dynamic dwelling stock model created, described and used by Sandberg et al. (2014a), Sandberg et al. (2014b), Sartori et al. (2016) and Sandberg et al. (2016a) was further developed with an energy analysis in Sandberg et al. (2016b) to estimate the Norwegian dwelling stock historical energy demand. The model consists of two parts as shown in Figure 7 where the first part is the building stock model already described here in chapter 2.2.2. However, the distribution of segments to three archetypes based on renovation states is a new element added to the model in Sandberg et al. (2016b). Three segments are used and those are Single Family Houses (SFH), Terraced Houses (TH) and Multi Family Houses (MFH). Dwellings are also distributed to nine cohorts after year of construction. The second part is the building stock energy model where segment specific floor area and cohort and archetype specific energy need intensities are applied to calculate the energy need per segment. Heat pump contribution is then calculated to find the delivered energy to the system. Use of energy carriers are estimated per segment and for the total stock. An adaption factor of measured over calculated annual energy demand is applied to simulate user behavior changes.

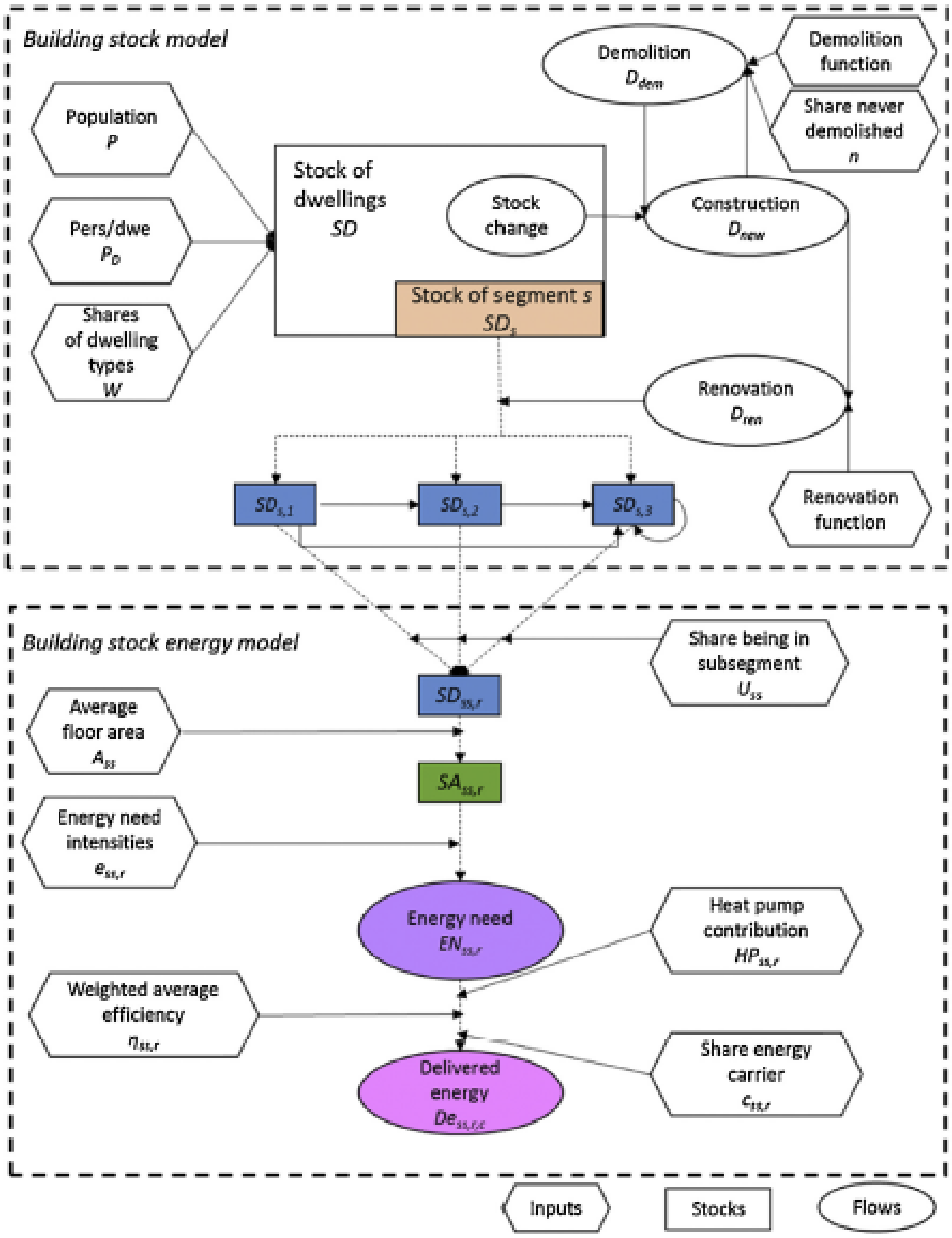


Figure 7: Conceptual outline of the building stock model and the building stock energy model. Hexagons represent input variables, rectangles represent stocks and ovals represent flows. All inputs and outputs are time-dependent (Sandberg et al., 2017).

Sandberg et al. (2016b) estimated the historical energy use in the Norwegian dwelling stock from 1960-2015 for a baseline scenario attempting to mimic the actual historical development as close as possible and six additional scenarios. The results showed that energy savings had taken place during the period and that shifts had happened to increase the energy efficiency of heating systems. A large increase in the population and heated floor area had led to an increase in total energy demand despite a stable energy intensity per m^2. The developed dynamic building stock energy model was shown to be suitable for explaining the historical demand of the Norwegian dwelling stock's energy demand.

A scenario analyses of future Norwegian dwelling stock energy demand was then done by Sandberg et al. (2017). A thermal adaption factor was applied per IPCC RCP 4.5 scenario predictions. A trendline was estimated based on statistics of technical estimated and real energy demand which implied that in very energy efficient buildings the average real energy use was higher than the theoretical estimate. In very inefficient buildings the average real energy use is lower than the technical estimate. The turning point for this adaption factor was estimated to be at about 100kWh/m^2 where average real and measured demand where equal. The scenario analysis was performed for a baseline business as usual scenario and 6 additional scenarios building on the baseline scenario but using combinations of three alternative development paths. The advanced renovation scenario assumed that renovated buildings would reach a better energy efficiency than in the baseline scenario. The extensive HP and PV scenario assumed a large implementation of HPs and PVs after 2020 and the frequent renovation scenario assumed a renovation cycle of 30 years. The minimized delivered energy scenario was a combination of all the considered variants. Scenario results found by Sandberg et al. (2017) are given in Figure 8 and clearly shows that the largest decrease in delivered energy to the system is expected through extensive use of local energy sources. A combination of all considered measures will decrease the delivered energy even more. Only a share of the stock is expected to be target for energy efficiency improvements of the building envelops up to 2050. 50% of the 2020 stock will be unchanged towards 2050 as they do not have a natural need of renovation. User behavior was also shown to be an important factor that might prevent policy targets from being met and could potentially reduce the expected energy saving potential from 51% to 36%. It was concluded that efforts should be made to counterwork this expected rebound effect.

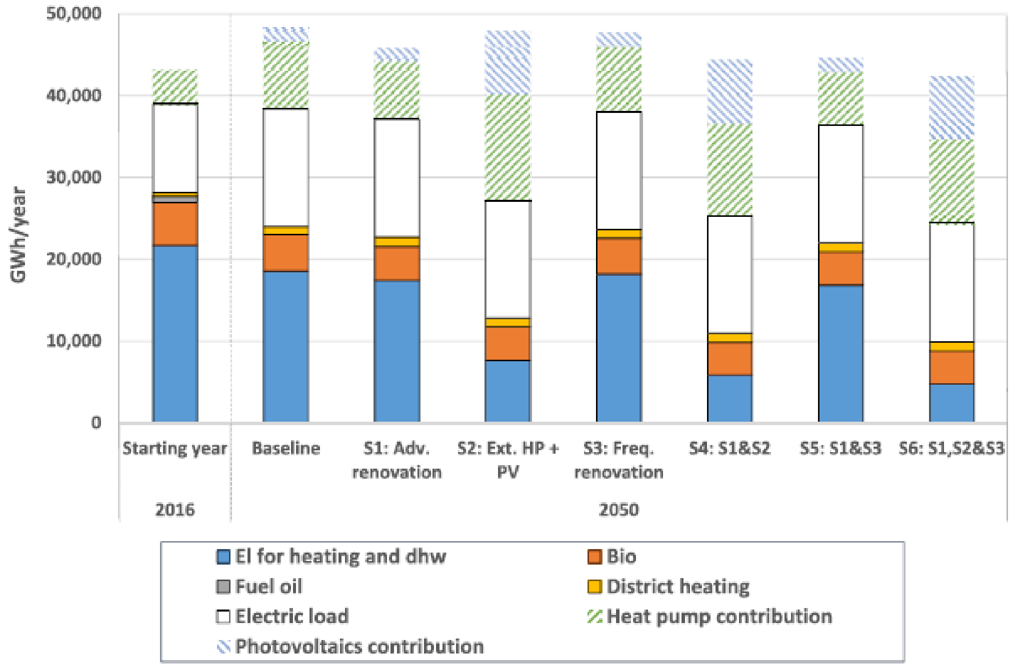


Figure 8: Energy mix in 2016 and in all scenarios in 2050. Estimated 'real' total delivered energy. The net thermal delivered energy equals the sum of electricity for heating and dhw, bio, fuel oil and district heating. The total net delivered energy also includes electric load. The local energy used in each scenario is the sum of 'Heat pump contribution and 'Photovoltaics contribution'. (Sandberg et al., 2017)

2.4 Trondheim studies

The municipality of Trondheim has a goal of becoming a low energy society where passive houses and where an environmental friendly consumption of materials is the standard (Trondheim Kommune, 2010). It is of high importance to reduce the energy use from the existing building mass. To reach these targets all new municipal construction must be done according to low energy standards. Construction projects involving buildings that should meet the passive house standard should be completed.

According to Trondheim Kommune (2010) the municipality of Trondheim has the highest possibility of reducing the energy use in Trondheim by using the municipality's role as a planning authority. Urban development projects have been started up such as the Brøset project that is trying to develop the Brøset area to a climate neutral city district with low GHG emissions. The project is supported by research groups from NTNU/SINTEF. The vision for the Brøset project is that this should become an attractive and provident district with less than 3 tons of CO_2 emissions per capita per year.

To increase the energy use efficiency in Trondheim a densification policy on the urban environment is implemented. Densification results in smaller dwelling area and a larger percentage of TH and MFH houses. The densification policy also increases the possibilities of using district heating or other renewable energy sources (Trondheim Kommune, 2010). A new planning- and buildings law is going to re-implement requirements for an independent building control. This could contribute to a higher share of new constructions is going to reach the energy requirements set by the building technical regulations (TEK). Another measure that is going to be considered is to set higher requirements to builders of major developments to create energy- and GHG accountings and is expected to increase focus on improving energy solutions on the developer side. According to Trondheim Kommune (2010) professional tools to create energy budgets for development projects already exists and models to estimate the climate impacts of building development projects is under development. These tools should be considered applied in Trondheim. It is also considered to actively use specific criteria of climate friendly buildings when it comes to the use of energy and materials, building methods and transports for pilot projects. Additionally, a top price system for electricity is going to be implemented where the price of electricity follows the actual consumption progressively. This might help raise awareness of what energy is used for and how much energy an individual is using at a given time. A regional center of efficient energy use, energy supply and technical energy solutions is considered established. This should make it easier for consumers and construction firms to use new and existing technologies that can give energy- and environmental gains. Lastly, Trondheim has a considerable amount of old wood furnaces that are inefficient in its energy use. Trondheim Kommune is working for a subsidizing policy for clean burning furnaces to be implemented.

2.4.1 District heating in Trondheim

District heating in Trondheim started up in 1982 when the city council approved the construction of a district heating incinerator at Heimdal. As of 2010 more than 6000 dwellings and 600 companies was covered by district heating which accounted for more than 30% of the total heating demand in Trondheim (Trondheim Kommune, 2010). Future growth of district heating in the city depends on "Energiloven" and its decisions regarding concession areas together with the municipality's statute on district heating connections. A map showing the current concession area is given in Figure 9.

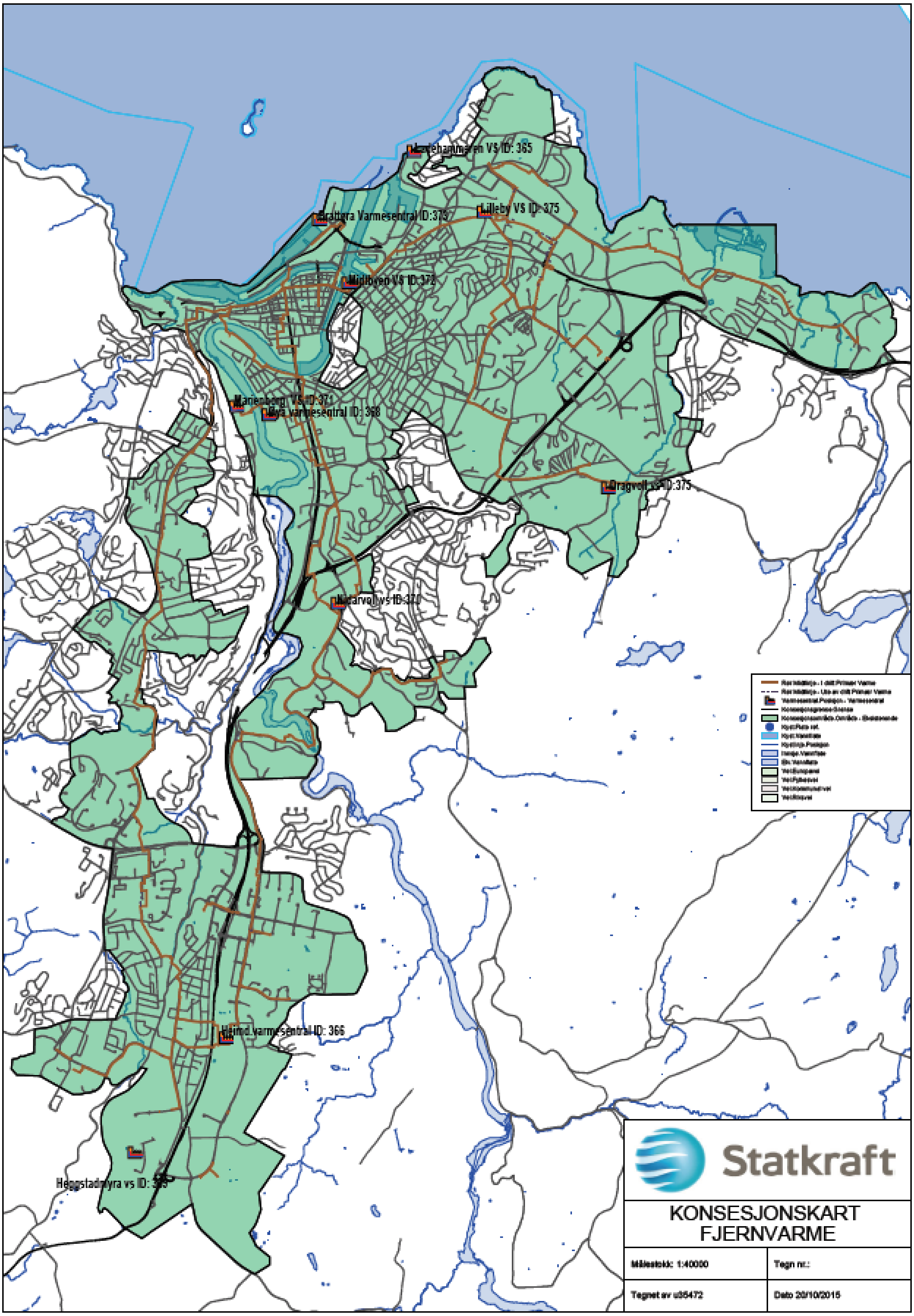


Figure 9:Concession area for district heating in Trondheim (Statkraft, 2017)..

Trondheim has an active policy of increasing the concession area for district heating as the city grows (Trondheim Kommune, 2010). Hydronic heating is a requirement for buildings to make use of district heating and the municipality of Trondheim has no means to impose builders to include this in new construction if it takes place outside of the concession area. However, it is possible to implement requirements that all new construction should be designed allowing for future expansion of the district heating system such that the necessary area to construct pipelines etc. must be available. The total GHG emission savings from the implementation of district heating depends on the energy mix used in the heating plant. The most important heating plant in the district heating network in Trondheim is the plant at Heimdal. The Heimdal plant has been operational since 2007 and had by 2010 increased the energy share of waste from 50% to 70-80% (Trondheim Kommune, 2010). The energy shares from sources like oil, gas and electric boilers decreased accordingly. Trondheim Kommune (2010) estimated that about 1600 oil boilers were in operation in the municipality in 2010 which represents around 10% of the stationary energy use for all purposes.

3. Methodology

In this section the methodology used in the thesis is explained in detail. First the principles of material flow analysis are explained. Then the case study city of Trondheim is studied before all input data and parameters are presented.

3.1 Material Flow Analysis

A dynamic material flow analysis model is applied to produce an analysis of the dwelling stock towards 2050 in Trondheim municipality. A material flow analysis (MFA) can be defined as a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2004). An MFA use the law of the conservation of matter to produce controlled results by simple material balance comparing inputs, stocks and outputs of a process. The method is attractive as a decision supporting tool in resource management, waste management and environmental management.

In the MFA methodology the term material represents substances and goods where substances are chemical elements while goods are substances or mixtures of substances that have economic market values (Brunner & Rechberger, 2004). However, goods are in MFA terminology only material goods and does not include immaterial goods such as energy, services or information. Processes are defined as a transport, transformation or storage of materials. Stocks are material reservoirs within the defined system. Flows of mass per time and fluxes of flows per cross section area links processes. Across system boundaries flows and fluxes are called imports or exports, while they are called inputs and outputs across processes. A set of material flows, stocks and processes within a defined boundary is called a system. System boundaries are defined in time and space and could consist of geographical borders or virtual limits. After defining the system boundary time other criteria as objectives, data availability, appropriate balancing period, residence time of materials within stocks and other parameters must be considered. An example of a MFA system is shown in Figure 10.

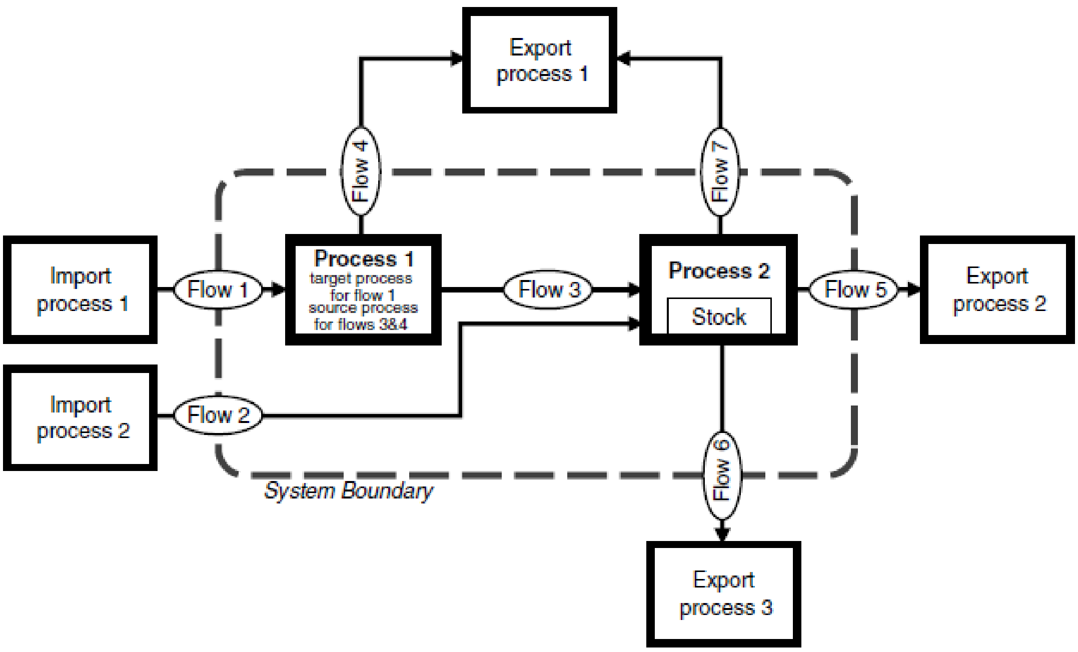


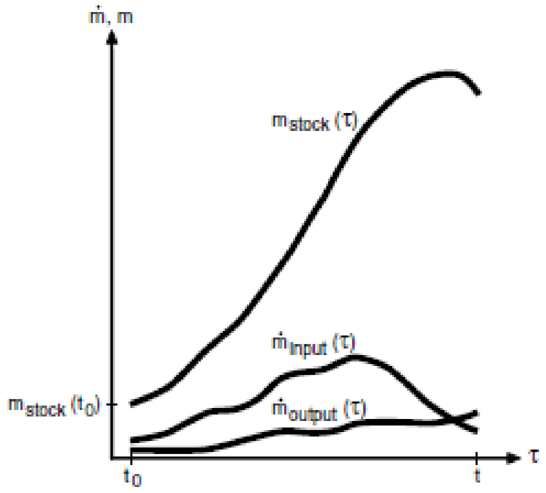
Figure 10: An example of an illustrated MFA system (Brunner & Rechberger, 2004).

Brunner & Rechberger (2004) defines the objectives of an MFA to be to delineate a system of material flows and stocks using well-defined uniform terms and reduce the complexity of the system as much as possible while still guaranteeing a basis for correct decision making. Relevant stocks and flows can be assessed in quantitative terms and thereby applying the balance principle and revealing sensitivities and uncertainties. Results will be presented in an understandable and transparent way describing flows and stocks of a system. The MFA results can be used as a basis for resource, environmental and waste management. Potentially harmful or beneficial accumulations or depletion of stocks can be detected and predicted across time. Priority setting of potential measures for environmental protection, resource conservation and waste management can be assessed. Goods, processes and systems can be designed to promote environmental protection, conservation of resources and management of waste.

Static MFA use an evaluation technique for identifying material flows and stocks within boundaries that are spatial and temporal. It uses material balances of inputs, stocks and outputs. Dynamic MFA however quantify past material flows, establish material flow patterns and apply the lifetime of materials in order to track temporal material flow changes (Park et al., 2011). A dynamic MFA involves considering future developments as a consequence of past activities (Sartori et al., 2016). Dynamic MFA modelling gives a better understanding of long term changes of resource demands and waste generation. Stocks of service units can be used as drivers for the material flows (Müller, 2006).

Amount of materials in stock can be assessed in two ways (Brunner & Rechberger, 2004). The first way is to determine the total mass of the stock by direct measurement of the mass or by assessing the volume and density of the stock. This method is normally used in cases where stocks do not change significantly for long periods like for instance stocks in natural processes like soils or large lakes. The second way can be applied to fast changing stocks when the size of the stock at an initial time t_0 is known. The magnitude of the stock can then be calculated by the difference between input and outputs for a given time span (t_0-t). $\dot{m}_{input}$ and $\dot{m}_{output}$ are usually functions of time and the stock m_{stock} can be calculated for any time t by applying Equation 1 (Brunner & Rechberger, 2004). An example of a calculation done by using these parameters is shown in Figure 11.

$$m_{stock}(t) = \int_{t_0}^{t} \dot{m}_{input}(\tau)d\tau - \int_{t_0}^{t} \dot{m}_{output}(\tau)d\tau + m_{stock}(t_0) \qquad (1)$$



The model used in this article is the same as used by Sandberg et al. (2014). It describes long term dynamic stock demand and activities such as construction, renovation and demolition within the system. It is applied for both segments of the stock and the total dwelling stock. Segments are given by dwelling type and construction period (cohort).

Figure 11: The stock of a nonsteady-state process. In order to calculate m_{stock} the functions $\dot{m}_{input}$ and $\dot{m}_{output}$ must be known (Brunner & Rechberger, 2004).

3.2 Trondheim case description

This case study is performed for the Norwegian city of Trondheim which has the third largest population size in Norway and is located in the middle of the country. The stock model analysis is done in a timeframe starting in year 1800 based on statistical data to present day and modelling towards 2050. The energy analysis is done for the period 1960-2050. Geographically the analyzed system is defined as the borders of Trondheim municipality as of present day in 2016. The borders of Trondheim municipality have changed several times since year 1800. The geographic area of Trondheim municipality is normally for statistical purposes split further into either 4 administrative city districts, 24 subareas, 41 school districts or 433 smaller districts (Eierskapsenheten Trondheim Kommune, 2012). A map showing the current geographic area of Trondheim municipality is shown in Figure 12.

Figure 12: Map showing the geographic area of Trondheim municipality (Adressavisen, 2015).

Data for the historical population of Trondheim municipality has been collected from Statistics Norway (2016b). The collected data are given for specific years between 1800 to present day only. Statistics Norway (2016b) has also provided data for historical buildings. As the historical Trondheim Municipality, geographically has changed over the years this has led to some difficulties in finding all the needed data from the 19th century. This has led to the need of making some assumptions and those are described in further detail later. The office of maps and surveying at Trondheim municipality (Kart og Oppmålingskontoret, 2016) has provided detailed statistics of the current building mass in Trondheim from Matrikkelen. However, this data corresponded to both buildings in use and not in use so it represented a problem to identify the in-use dwelling stock. Therefore, data from Statistics Norway (2016b) has been prioritized in the dwelling stock model input.

3.3 Input data and parameters

Different input data and parameters to the model is described in this section. For the dwelling stock model input the parameters needed are the population in Trondheim split into time series for two segments of detached and compact dwellings, persons per dwelling for the two types, renovation cycles and dwelling lifetime distribution. For the energy analysis input parameters include floor area per dwelling, energy intensities, PV intensities, PV shares, HP shares, system efficiencies, energy mix shares and dhw intensity. Scenario analysis is run for different input data in chapter 3.4. Additionally, corrections for historical and future expected heating degree days and thermal adaption factors are included in the estimations as described in chapters 3.5 and 3.6.

3.3.1 Population data

Population is one of the main drivers for the model that creates the need for housing. Statistics provided by Statistics Norway (2016a, 2016b) has been used to create the input time series. Data are not available for the whole series, but can be found for approximately every ten years since 1801 to present day. Some selected data is presented in Table 1 below.

Table 1: Population of Trondheim from selected censuses (Statistics Norway, 2016a, 2016b).

Year	**1801**	**1825**	**1845**	**1865**	**1900**	**1920**	**1946**	**1960**	**1980**	**2001**	**2011**
Population	13681	17456	21755	27748	47176	71342	88171	105194	134854	151198	176133

Forecasts for the population in Trondheim municipality towards 2050 has been provided by Trondheim kommune & Byplankontoret (2016) for three scenarios, one reference medium growth scenario (baseline), one low growth scenario and one high growth scenario. The forecasts are developed by Trondheim kommune using the forecast program Kompas and are based on assumption for fertility rates, death rates, immigration patterns and dwelling construction. The uncertainties in the forecast increases the further out in the future it goes and future fertility rates and moving patterns could take several directions (Trondheim Kommune, 2016). The different scenarios are shown in Figure 13.

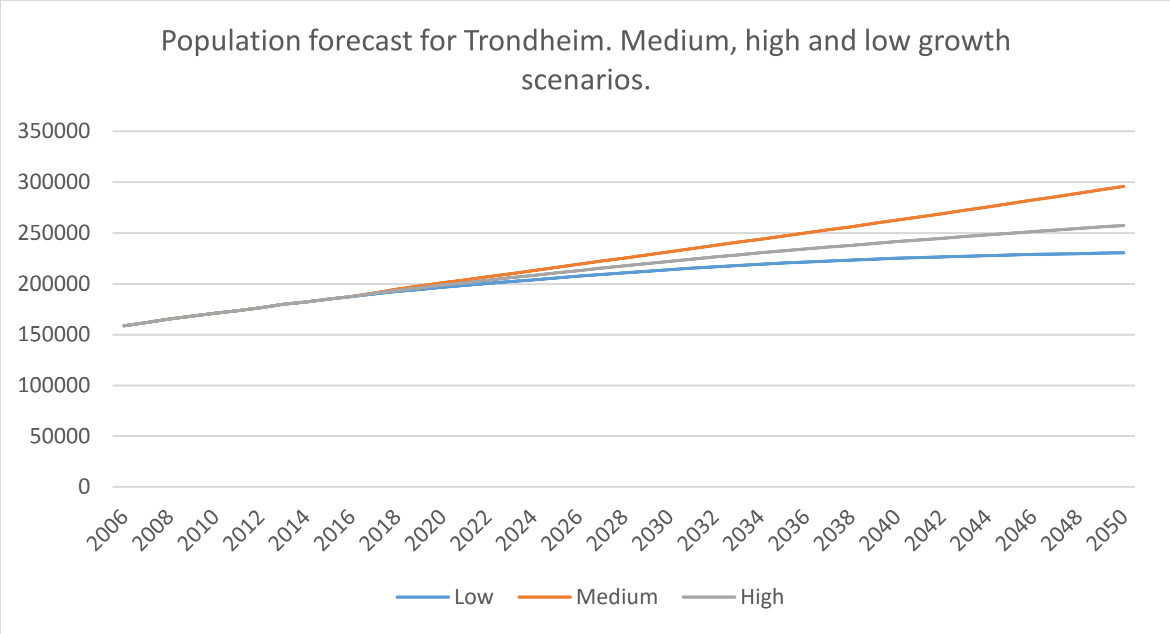


Figure 13: Population forecasts from present day towards 2050 for different population growth levels.

To fill the holes in the time series and create a smooth input curve non-linear Sigmoid 4 regression has been used. By smoothing input data fluctuations can be removed from the results. The resulting smoothed population curve is plotted together with obtained population data from censuses and the population forecast assuming medium population growth in Figure 14.

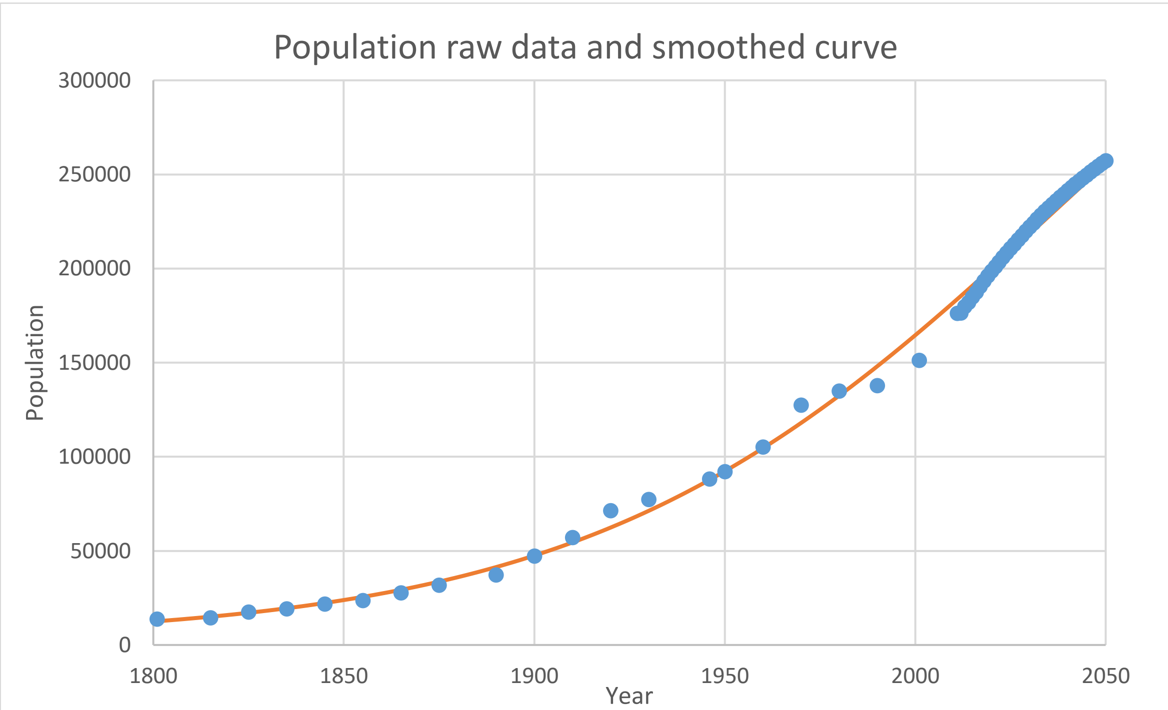


Figure 14:Smoothed Sigmoid 4 non-linear regression curve for the population of Trondheim between 1800-2050 and obtained data from censuses and forecasts assuming medium population growth.

After creating a time series for the population in Trondheim it was needed to split the population vector in two segments. Firstly, the historical and estimated future population for detached houses and secondly the same for compact houses. From 1970 to 2001 detailed data on population shares living in both compact and detached dwellings is available at Statistics Norway (2016b). Before 1970 some data is available in old population censuses from Statistics Norway (2016a), but other definitions is used and some parameters are missing. It has been assumed that before 1901 all the population located outside the city center of Midtbyen was living in detached dwellings. For Midtbyen it is assumed that 25% of the population was living in compact dwellings which corresponds to previous studies done on the national level by Sandberg et al. (2014). After 1900 a linear increase in the population share of compact dwellings towards the 1970 levels of 28% was assumed giving the results in Table 2. There is a rapid growth in the compact population from 7% in 1801 to 19% in 1845 and then down to 17% in 1876. After 2001 it is assumed a steady share of compact dwellings towards 2016 and further towards 2050. The values shown in Table 2 were then used to model and plot the split of the population in Trondheim living in compact and detached dwellings. This is shown in Figure 15. The figure shows clearly that although the total number of people living in the two dwelling types will increase, the share of the population living in compact dwellings has grown from 7% in the 1800 to 32% today and is assumed to stay at 32% towards 2050.

Table 2: Population dataset before non-linear regression with medium growth.

Year	Total population	Population detached	Population compact	Population share detached	Population share compact
1801	13681	12660	1021	93 %	7 %
1845	19163	15468	3695	81 %	19 %
1876	31730	26192	5538	83 %	17 %
1900	47176	37513	9663	80 %	20 %
1930	77222	59461	17761	77 %	23 %
1946	88171	66128	22043	75 %	25 %
1950	92144	68187	23957	74 %	26 %
1960	105194	78895	26299	73 %	27 %
1970	127328	94799	32529	74 %	26 %
1980	134854	93410	41444	69 %	31 %
1990	137846	98401	39445	71 %	29 %
2001	151198	108076	43122	71 %	29 %
2011	176133	120293	55840	68 %	32 %
2016	187353	127956	59397	68 %	32 %
2025	210613	143842	66771	68 %	32 %
2040	241360	164841	76519	68 %	32 %
2050	257320	175741	81579	68 %	32 %

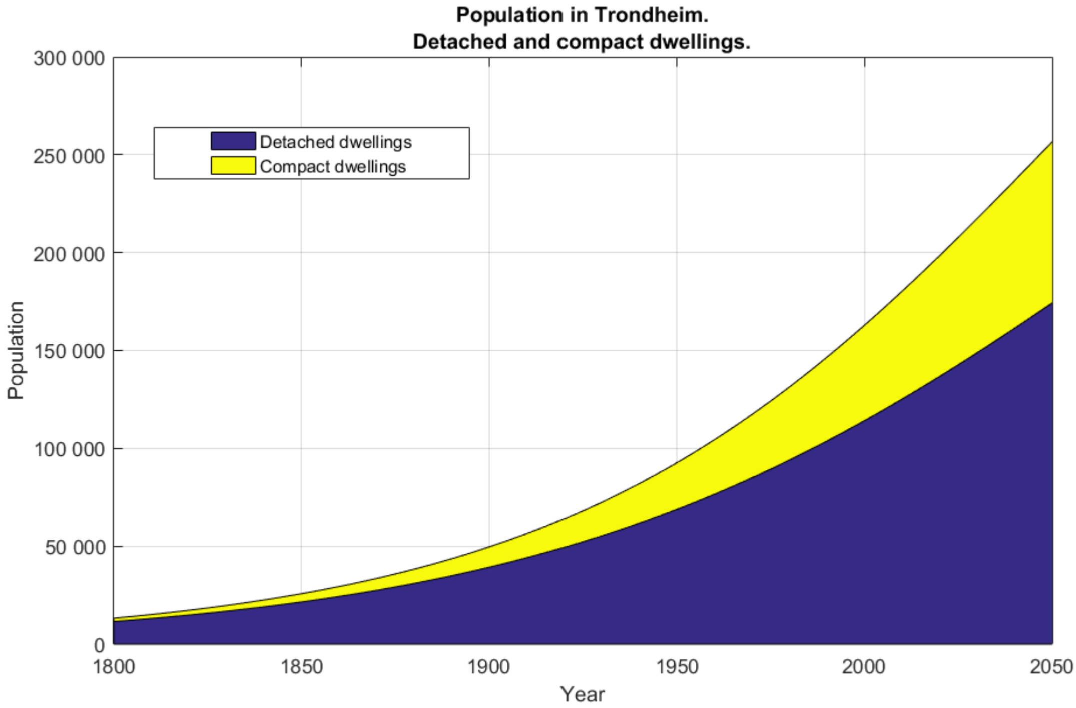


Figure 15: Smoothed Trondheim population baseline input for detached and compact dwellings.

3.3.2 Students in Trondheim

Trondheim is a city with a large percentage of students and in 2015 there were 35474 students at the universities and colleges in the city. According to Asplan Viak (2014) and Byplankontoret (2016) the percentage of students registered at higher education in Trondheim that was not registered as inhabitants in Trondheim municipality was 60%. At the same time, it was estimated that about 20% of the students is not living in Trondheim municipality while studying. This means that the official numbers of the population in Trondheim has been underestimating the actual population in Trondheim as students' needs to be registered to be counted in statistics. Asplan Viak (2014) has calculated that in 2013 there was 28142 students living in Trondheim out of which a share of 48% calculated to 17518 students is officially registered as inhabitants in another municipality in Norway. This means that in 2013 there was an actual estimated 17518 inhabitants extra than the given number of students from official statistics for Trondheim according to Asplan Viak (2014).

Yearly data giving the number of students from year 2000 to present day at higher education in Trondheim is available at Table 03814 at Statistics Norway (2016b). Before year 2000 no data is available at this source, but data has been found for specific years. According to Telhaug (1994) there was about 1000 students at NTH Trondheim in 1945. At the end of the 1970s there was 15 institutions of higher education in Trondheim. In 1984 the number of students is given as 12266 out of which 9150 students belonged to NTH and AVH corresponding to 75% of the total (Kultur- og vitenskapsdepartementet, 1985). Data is given in 1973, 1980 and 1983 for NTH and AVH, and assuming the same share of the city's students at these two institutions the total number of students can be calculated. A selection of gathered data is given in Table 3.

Table 3: Selected gathered data of the number of students registered at higher education in Trondheim.

Year	**1945**	**1973**	**1980**	**1984**	**2000**	**2010**	**2015**
Students	1000	8666	10910	12266	25420	31068	35474

By using the same assumptions as Asplan Viak (2014) and Byplankontoret (2016) mentioned above the number of students living in Trondheim without having a home address registered in the municipality can be estimated. Byplan Byplankontoret (2016) has also forecasted that the number of students in Trondheim in 2025 will grow to 38358. By using this assumption together with collected data, the number of students in the city has been estimated as given in Figure 16. The grey line representing the students going to higher education in Trondheim and living outside the city. The orange line represents students at higher education living in Trondheim but being officially registered as inhabitants elsewhere. The grey and the orange line sums up to the yellow line representing the total number of students at higher education in Trondheim that are not officially registered as inhabitants in the city which is 60%. The blue line represents the total number of students at higher education in Trondheim. The difference between the blue and the yellow line then represents the total number of students that are officially registered as inhabitants in the city and sums up to 40% of the total. The orange line giving students living in Trondheim and not registered as official inhabitants is later added to the population data to create a student correction in the delivered energy sensitivity estimations.

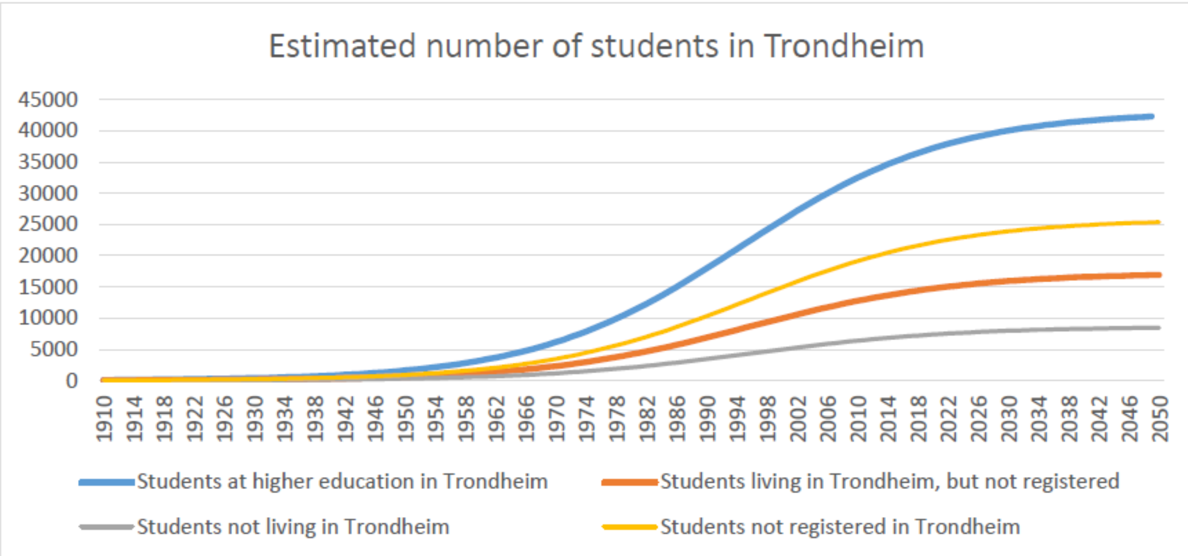


Figure 16: Estimated number of students at higher education in Trondheim from 1910 and towards 2050.

The city center Midtbyen has a very large share of students (Eierskapsenheten Trondheim Kommune, 2012). The school districts of Bispehaugen, Eberg, Singsaker and Kalvskinnet all have a share of students above 30%, with Kalvskinnet having the largest share of student inhabitants with 40%. These areas are all close to the city center and it shows that students prefer to live close to the city center. An overview of the where students in Trondheim lives is given in Figure 17.

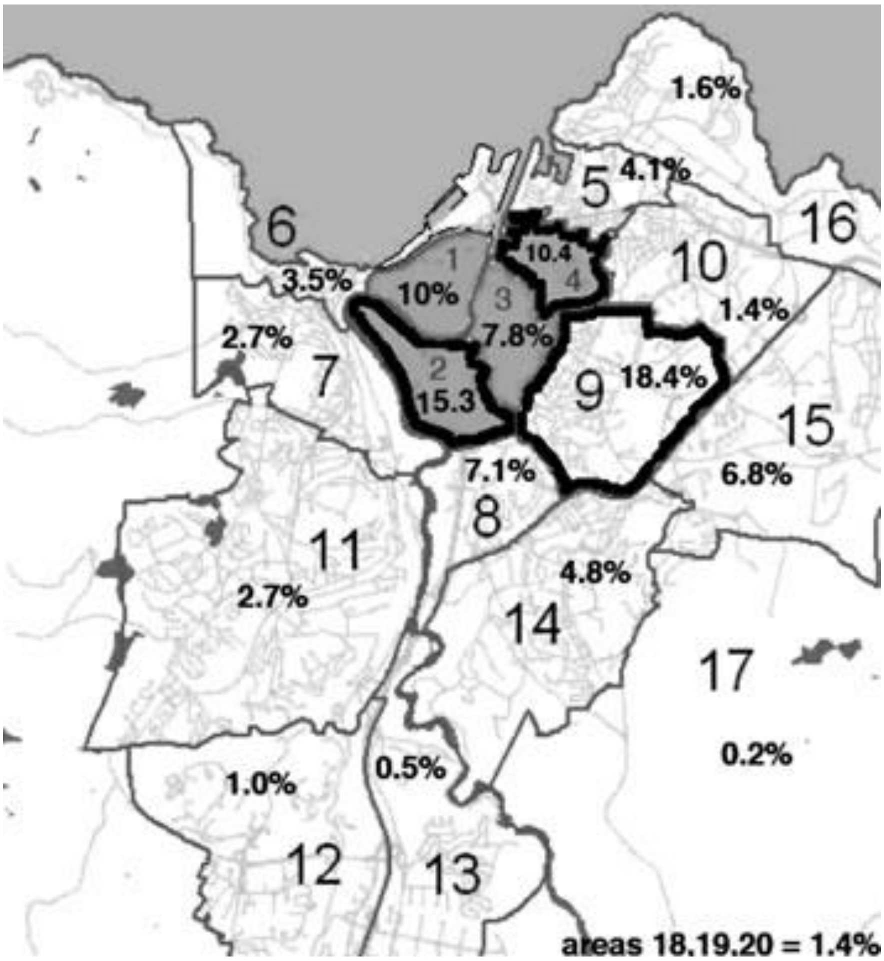


Figure 17: Percentage of students living in the different subareas of Trondheim (Thomsen & Eikemo, 2010).

More than 60% of the students live in the areas of Midtbyen (1), Øya-Elgseter (2), Singsaker (3), Bakklandet-Møllenberg (3 & 4) or Moholt (9). Combining this information with data on building types for different areas in the city from Eierskapsenheten Trondheim Kommune (2012) given in Table 4 estimations can be made for the share of students living in compact buildings.

Table 4: Share of compact dwellings in different selected areas in Trondheim (Eierskapsenheten Trondheim Kommune, 2012).

Area	**Singsaker (3)**	**Midtbyen (1)**	**Øya-Elgseter (2)**	**Bakklandet-Møllenberg (3 & 4)**	**Moholt (9)**	**Trondheim average**
Share compact dwellings	69%	65%	56%	73%	36%	36%

Table 4 combined with Figure 17 shows that students have a different way of living than the rest of the population and it can be assumed that a higher share of students live in compact buildings than the general population. For the calculations performed considering students it is assumed that 50 % of the students live in compact buildings.

3.3.3 Person per dwelling

The numbers of persons living per dwelling P_D historically and towards 2050 is also important for the model as it is needed to calculate the number of dwellings in the stock. In order to make estimations data from old censuses provided by Statistics Norway (2016a) has been examined. Work on this has previously been performed on the national level by Sandberg et al. (2014). Before 1900 very limited data has been found for the P_D in Trondheim and the statistics use the term "households" instead of dwellings. It was assumed for 1801 and 1846 that the share of total households in Strinden fogderi that belonged to the later municipalities of Strinden, Tiller, Bynesset and Leinstrand is 50 % which corresponds to more detailed data found in 1876 and then added up with data for Trondheim. From this the average number of persons per household $P_{Household}$ has been calculated. Some data on the total number of houses is available as well at Statistics Norway (2016a) and the total number of persons per house P_H has been calculated. Houses seems to correspond with a building with different number of households belonging to it. A summary of selected data in the period from 1801-1900 is given in Table 5.

Table 5: Total houses, households, persons per household and persons per house based on data from Statistics Norway (2016a).

Year	Population	Total houses	Total households	P_{House}	$P_{Household}$
1801	13681	-	4087	-	3,35
1846	19163	3908	-	4,90	-
1876	31730	3621	6533	8,76	4,85
1900	47176	4552	13022	10,3	2,44

From Table 5 the number of total houses seems to decrease from 1846 towards 1876 before increasing again to 1900. This results in a P_{House} that increase a lot and as the P household does not change nearly as much it seems unreliable. This indicates an uncertainty of whether the gathered P_{House} or $P_{Household}$ data corresponds to persons per dwelling P_D and that the definitions of houses and households might have changed over time during the 19th century. As no better estimation has been found it has been assumed that the P_D of Trondheim of the period 1800-1900 is equal to the national level used in Sandberg et al. (2014).

For 1930 and 1950 dwellings data has only been found for the pre 1964 municipalities of Trondheim and Strinda and therefore the absolute numbers of total dwellings are somewhat smaller than expected, but the average P_D calculation is based on this and the population of them. The P_D for detached and compact segments has been calibrated towards this. The term "apartments" is used instead of dwellings in this period, but they seem to correspond well and it is assumed to be equal to dwellings. Likely it is used for both compact and detached dwellings. From 1970 there are detailed data available for the whole present day Trondheim municipality up until 2001 (Statistics Norway, 2016a). For 2011 and 2016 no detailed data on the number of compact dwellings in use has been found as compact dwellings has been categorized together with semi-detached dwellings by Statistics Norway (2016b) for dwellings in use. Still there are numbers available for the total compact dwellings 2011 and 2016 from Statistics Norway (2016b) and for 2016 from Matrikkelen provided by Kart og Oppmålingskontoret (2016). Assumptions has been done based on a similar share of compact dwellings of in use as not in use total dwellings. Towards 2050 it is assumed a slight decrease in P_D for the average persons per dwelling corresponding to the national level assumptions done by Sandberg et al. (2014). A summary of the data for P_D can be found in Table 6 below.

Table 6: P_D dataset with found data and assumptions based on dwelling statistics before non-linear regression.

Year	Total dwellings in use	Detached dwellings	Compact dwellings	P_D average	P_D Detached	P_D Compact
1801	-	-	-	-	5,36	5,36
1846	-	-	-	-	4,93	4,66
1876	-	-	-	-	4,63	4,20
1900	-	-	-	-	4,40	3,81
1930	13092 [1]	-	-	4,02 [1]	4,20	3,61
1946	14069 [1]	-	-	3,92 [1]	4,05	3,50
1950	15687 [1]	-	-	3,54 [1]	3,70	3,30
1970	44555	31286	13269	2,82	2,91	2,61
1980	53164	34327	18837	2,51	2,68	2,20
1990	60407	40099	20308	2,26	2,51	1,76
2001	69101	45404	23698	2,17	2,39	1,70
2011	83344	50852	32492	2,11	2,34	1,63
2016	-	-	-	-	2,32	1,61
2025	-	-	-	-	2,32	1,59
2040	-	-	-	-	2,32	1,56
2050	-	-	-	-	2,32	1,55

Note: 1 Given values represents only the pre-1964 municipalities of Trondheim and Strinda and not the whole geographic area of today's municipality of Trondheim.

Sigmoid 5 non-linear regression was then applied on the P_D data to create model input vectors for the whole-time series. This gave an R^2 value of 0.9814 for the detached P_D and a R^2 value of 0.9727 for compact. Smoothed curves are plotted with raw input data in Figure 18. To perform a sensitivity analysis on the person per dwelling parameter P_D vectors was then smoothed with non-linear regression for respectively 10 % higher and 10 % lower P_D values after 2016 towards 2050. P_D has been plotted for three different levels for the period 1990 to 2050 in Figure 19. Due to the non-linear regression method used the different P_D curves in Figure 19 splits from each other earlier than the year 2016.

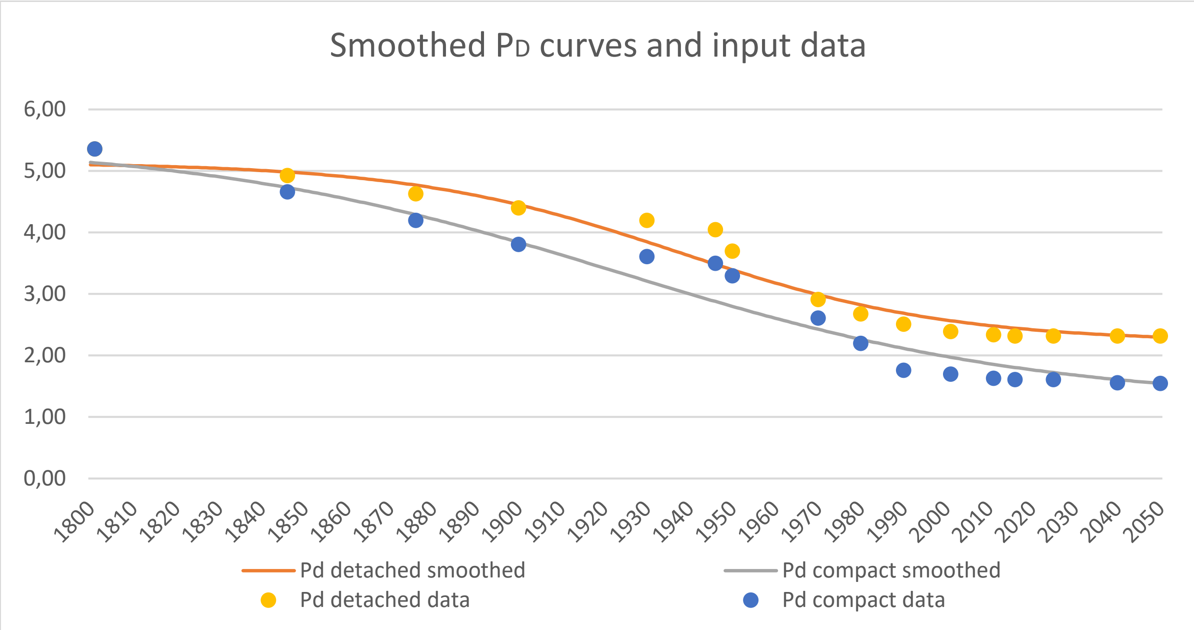


Figure 18:Plotted raw P_D data and P_D with smoothed curve from Sigmoid 5 regression.

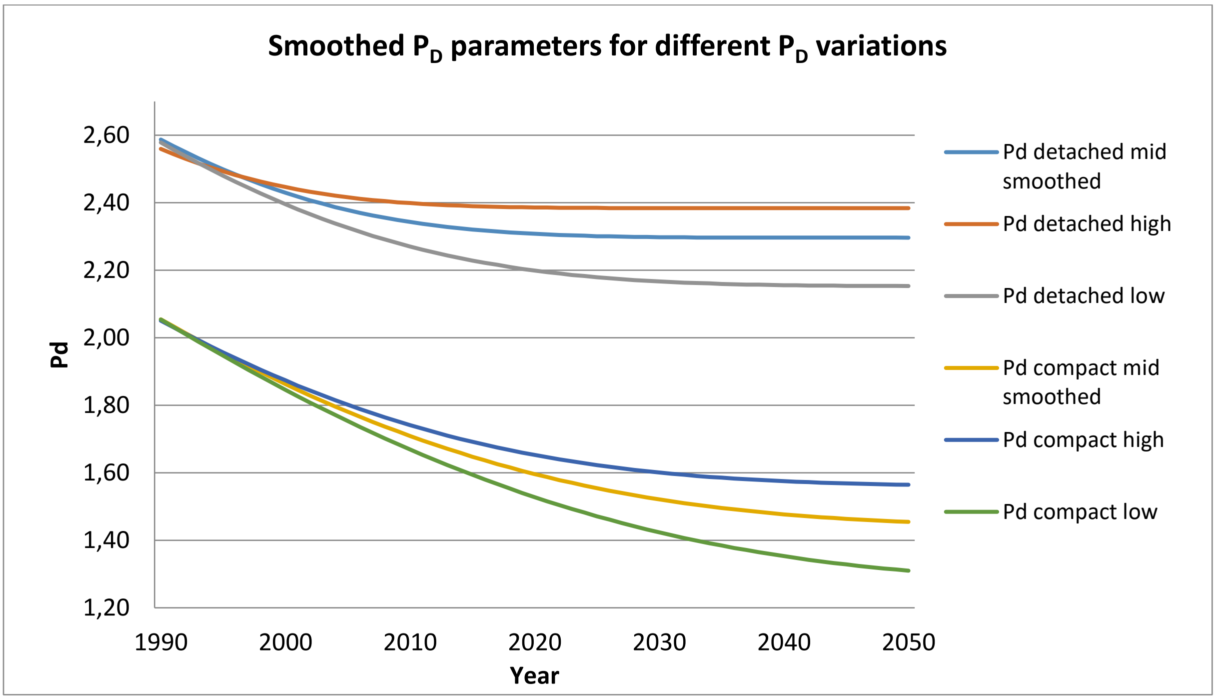


Figure 19: Plotted smoothed P_D for middle, high and low levels between 1990 and 2050.

3.3.4 Construction activity of dwellings in Trondheim

Data for the construction of new dwellings between 2006-2016 has been calculated from Table 06266 at Statistics Norway (2016b). It has been assumed that all newly constructed dwellings are occupied the same year even though the data covers both unoccupied and occupied dwellings. Data used for comparing model results with construction activity is given in Table 7.

Table 7: Constructed occupied and unoccupied dwellings yearly between 2008-2016 (Statistics Norway, 2016b).

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Constructed dwellings in total	1828	692	431	922	898	972	2109	1404	2081
Constructed detached dwellings	576	403	198	757	519	426	1058	472	985
Constructed compact dwellings	1252	289	233	165	379	546	1051	932	1096

The construction activity seems to differ and fluctuate a lot between years. At the highest the number of constructed dwellings was 2109 in 2014, while the lowest point was 431 dwellings constructed in 2010. A possible reason for the construction drop in 2009-2013 could be that the financial crisis that started in 2007 also made funding of new construction projects more difficult and affected the rate of new construction in Trondheim in this period.

3.3.5 Trondheim dwelling stock composition

Data was found on the composition of the dwelling stock in Trondheim in 1980 and 2011 in Table 06266 at Statistics Norway (2016b). The data for 1980 is given in Table 8 and data for 2011 is given in Table 9.

Table 8: Dwelling stock composition of Trondheim in 1980 (Statistics Norway, 2016b).

Cohort	Total	-1901	1901-1945	1946-1980	1981-2015	Unknown
Total dwellings	53164	3226	9619	38044	-	2275
Detached dwellings	34327	2244	6611	23503	-	1969
Compact dwellings	18837	982	3008	14541	-	306

Table 9: Dwelling stock composition of Trondheim in 2011 (Statistics Norway, 2016b).

Cohort	Total	-1901	1901-1945	1946-1980	1981-2015	Unknown
Total dwellings	92191	4297	10961	44458	30974	1546
Detached dwellings	56559	1635	6136	27151	20359	1278
Compact dwellings	35632	2662	4780	17307	10615	268

65% of the dwellings in Trondheim were detached and 35% compact in 1980. In 2011 the total share of compact dwellings has increased to 38 %. Strangely the number of total dwellings from before 1901 has increased and this could perhaps be partly explained due to the unknown category getting smaller. Another explanation could be that dwellings that were not in use in 1980 has now been occupied. To estimate the share of detached dwellings being SFH and TH dwellings data from Table 06266 at Statistics Norway (2017) was used. The number of SFH and TH dwellings in 2016 in Trondheim are presented in Table 11 after construction periods.

Table 10: 2016 SFH and TH dwellings in Trondheim and their corresponding shares after year of construction (Statistics Norway, 2017).

Construction period	SFH dwellings	TH dwellings	SUM dwellings	SFH (%)	TH (%)
-1900	330	1120	1450	23 %	77 %
1901-1920	487	1003	1490	33 %	67 %
1921-1940	929	3028	3957	23 %	77 %
1941-1945	109	83	192	57 %	43 %
1946-1960	2456	4985	7441	33 %	67 %
1961-1970	4294	4221	8515	50 %	50 %
1971-1980	3546	4051	7597	47 %	53 %
1981-1990	5193	2607	7800	67 %	33 %
1991-2000	2027	2170	4197	48 %	52 %
2001-2010	1499	2512	4011	37 %	63 %
2011-	1043	1051	2094	50 %	50 %
Unknown	401	337	738	54 %	46 %

3.3.6 Delivered energy

A summary of gathered data for historical delivered energy from oil, biofuels and district heating to dwellings in Trondheim Municipality is given in Figure 17. For oil and biofuels all data has been provided by different sources within Statistics Norway and has been put under the same tag in Figure 20. They are explained more in detail in chapter 3.3.6.3 later. Years where data has been obtained for all energy carriers has been limited to the years 2004-2008. This is because Statistics Norway stopped publishing statistics of delivered energy on the municipal level in 2009. Additionally, no data for delivered electricity has been found for years before 2004 on the municipal level. The calculated energy mix for the period is presented in Table 11.

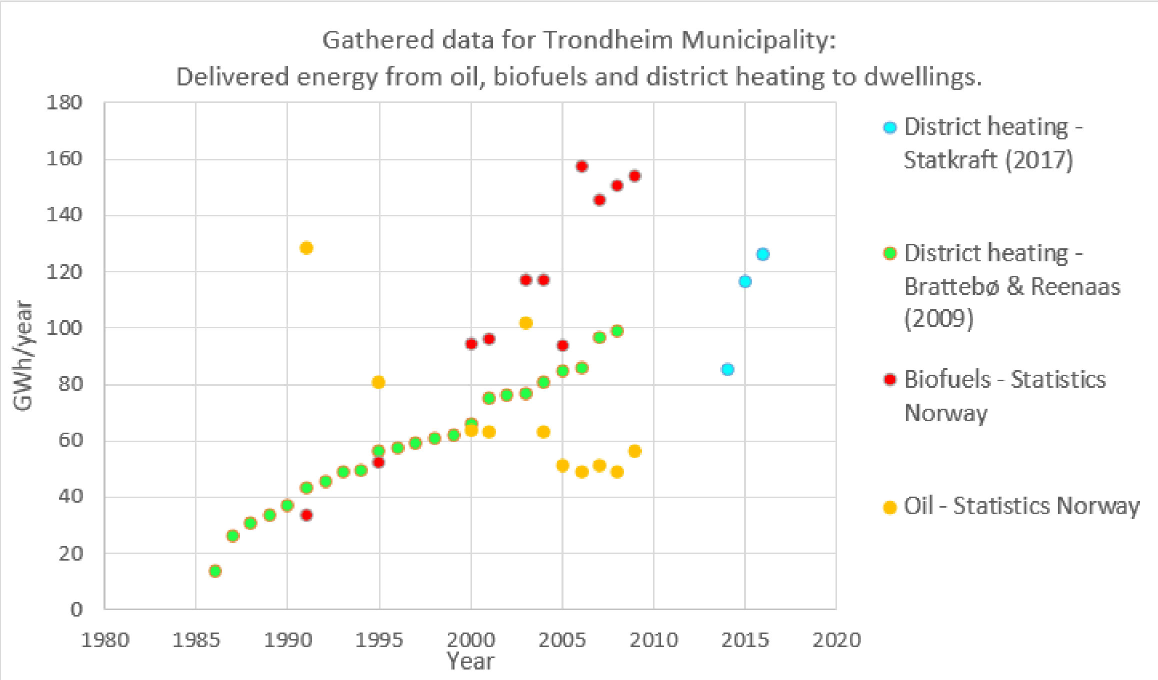


Figure 20: Gathered data for Trondheim Municipality, delivered energy to dwellings from various sources.

Table 11: Calculated energy mix for the whole Trondheim municipality based on gathered data for the period 2004-2008.

	Electricity	Oil	Biofuels	District heating
2004	80,4 %	4,8 %	8,8 %	6,0 %
2005	83,0 %	3,8 %	7,0 %	6,3 %
2006	78,9 %	3,5 %	11,3 %	6,2 %
2007	79,7 %	3,5 %	10,1 %	6,7 %
2008	78,6 %	3,5 %	10,8 %	7,1 %

Based on the shares presented in Table 11 it can be observed that the share of district heating seems to increase for the period, while the oil share is decreasing very slightly and then stabilizing. Biofuels and electricity is fluctuating around 10% and 80% respectively. Some winters are colder than others which could lead to change of peak loads and energy prices. This could be a reason for fluctuations in the energy mix shares or it could just be uncertainties. A further description on the gathered data for each energy carrier follows below.

3.3.6.1 Electricity to dwellings

Electricity represents the largest share of energy delivered to dwellings in Trondheim. Data on the municipal level has been found for the years 2004-2016. Before 2004 data for delivered electricity to dwellings was only available on the regional Trøndelag level. 2004-2015 data has been provided by Table 10314 and Table 06926 at Statistics Norway (2017) while 2016 data was provided by email from the electrical grid company Trønder Energi (2017). Gathered data is presented in Figure 21.

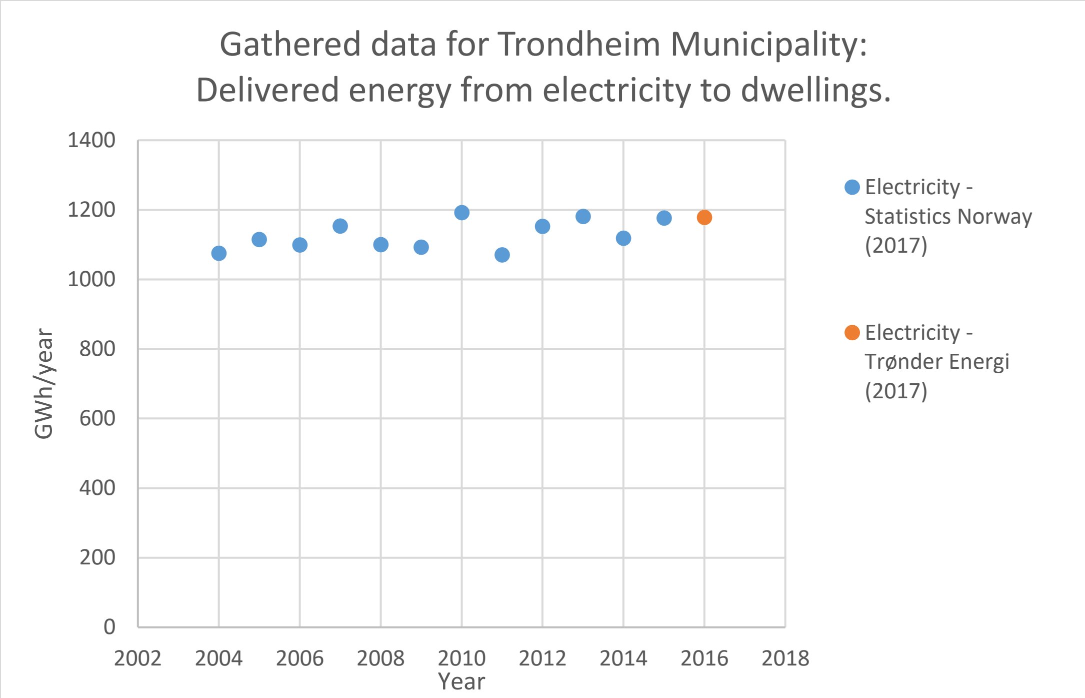


Figure 21: Gathered statistical data on delivered energy to dwellings from electricity for Trondheim Municipality.

The trend of delivered energy from electricity to dwellings in Trondheim seems to be quite stable with some natural fluctuations. 2011 is the year with the lowest delivered electricity with 1071 GWh while 2010 is the year with the highest delivered electricity with 1193 GWh. 2010 was also a very cold year with a deviation from the 1970-2000 mean temperature of -1.1 ◦C which explains the peak in delivered energy (Norwegian Meteorological Institute, 2017).

3.3.6.2 District heating to dwellings

District heating was introduced in Trondheim in 1982. Yearly statistics of supplied energy by district heating in Trondheim between 2014-2016 to private houses and housing cooperatives has been supplied by (Statkraft, 2017b) and is given in Table 12.

Table 12: Delivered energy to private houses and housing cooperatives from district heating and the corresponding shares of total delivered energy to dwellings for the period 2014-2016 (Statkraft, 2017b).

Year	**Delivered energy to private houses [kWh]**	**Delivered energy to borettslag [kWh]**	**Sum [GWh]**	**Share private houses (%)**	**Share housing cooperatives (%)**
2014	29591278	55543770	85.1	34.8 %	65.2 %
2015	35540882	80999861	117	30.5 %	69.5 %
2016	91171875	35397430	127	28.0 %	72.0 %

It has been assumed after discussions with Statkraft that "Borettslag" which translate to cooperatives in English is equivalent with compact dwellings and that private houses are equivalent with detached dwellings. Further it has been assumed an equal split in delivered energy from district heating to detached dwellings to the two segments SFH and TH dwellings.

For some of the years that statistics has been provided delivered energy are not specified as delivered to dwellings but rather all purposes in Trondheim Municipality. For instance, the statistics given by (Statkraft, 2017a) for the period 2010-2013 as shown in Table 13. It has then been assumed a constant share of total delivered energy for each year going to dwellings calculated by available data.

Table 13: Total delivered energy from district heating in Trondheim to all purposes (Statkraft, 2017a, 2017b).

Year	**Total delivered energy from district heating in Trondheim [MWh]**	**Percentage of delivered energy going to dwellings**
2010	642 266	n/a
2011	520 336	n/a
2012	599 946	n/a
2013	611 302	n/a
2014	626 905	15,0%
2015	573 468	20,3%
2016	569 264	20,2%

Data on total delivered energy from district heating in Trondheim and energy delivered specifically to dwellings can be found for the period 1986-2008 in the research done by Brattebø & Reenaas (2012). Calculations has then been done to find the average yearly share of delivered energy from district heating in Trondheim going to dwellings and results obtained are shown in Figure 22.

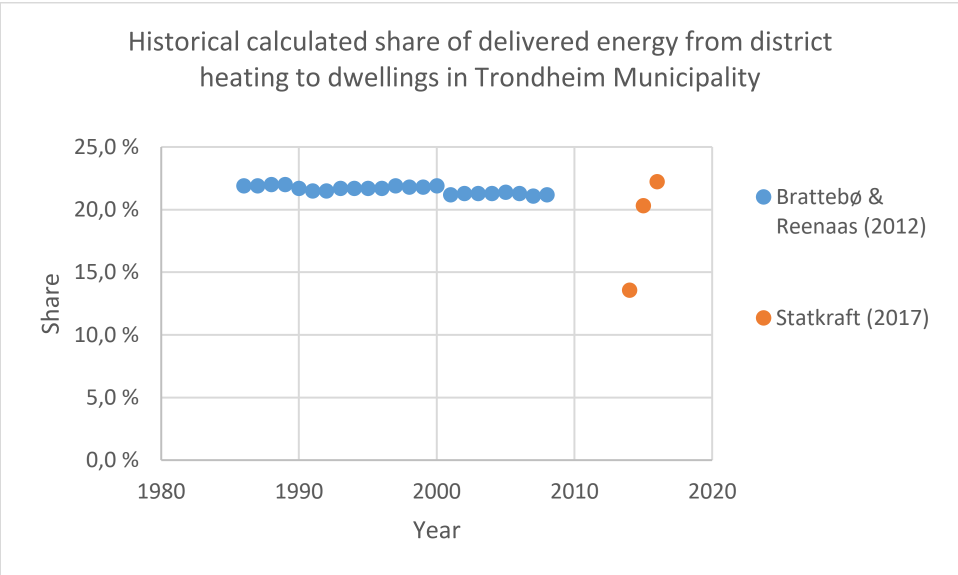


Figure 22: Calculated historical share of delivered energy from district heating to dwellings in Trondheim Municipality based on statistics from the given sources.

There seems to be a constant trend in the share of energy delivered to dwellings of the total delivered energy from district heating. The exception is the 2014 data where a drop to 14% can be spotted together with a large growth in delivered district heating to Trondheim. The reason for this has not been identified, but could potentially be because most of the large growth seen this year was due to non-residential buildings being added to the district heating system and not dwellings. If this is the case, then a larger share of the 2015 growth in delivered energy must have been residential projects. The average share of delivered energy going to dwellings for the period 1986-2016 has been calculated to 21% of the total delivered energy from district heating. Statkraft (2017b) has provided statistics of the yearly growth in district heating in Trondheim Municipality for all purposes for the years 2001-2016 as given in Figure 23.

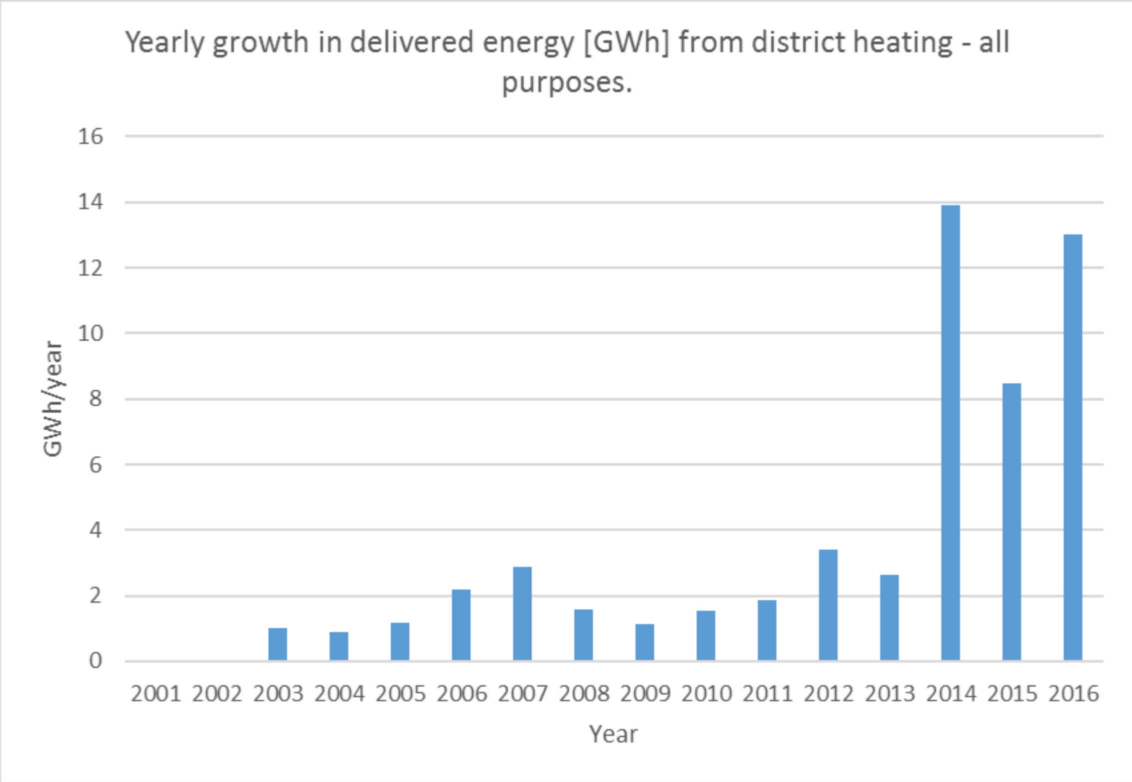


Figure 23: Historical yearly growth in delivered energy [GWh] from district heating to all purposes in Trondheim Municipality (Statkraft, 2017b)

For the coming years in Trondheim it is estimated a yearly new growth of 15-17 GWh which is in line with the growth experienced in 2014 and 2016 as shown in Figure 23 (Statkraft, 2017b). The large growth difference between pre-2014 and post-2014 could be explained by the construction of large new district heating projects to new dwellings like the Grillstad Marina project and other new large construction projects of commercial buildings.

Assuming a future share of new total delivered energy from district heating in Trondheim as the historical trend the new yearly growth of delivered energy from district heating to dwellings can be calculated. This gives a growth in the range of 3.2-3.6 GWh per year with an average growth of 3.4GWh per year. This can be further split into 1.1 GWh per year to detached dwellings and 2.5GWh per year to compact dwellings by assuming that 68% goes to compact dwellings.

3.3.6.3 Biofuels and oil to dwellings

Data for delivered oil and biofuels for Trondheim Municipality has been found for some specific years in the period 1991 to 2009. A summary of gathered data is given in Table 14.

Table 14: Gathered data of histroical delivered oil [GWh] and biofuels [GWh] to dwellings in Trondheim Kommune from various sources.

Year	Oil [GWh]	Biofuels [GWh]	Source
1991	129	33	Haakonsen et al. (2004)
1995	81	53	Haakonsen et al. (2004)
2000	64	95	Haakonsen et al. (2004)
2001	63	96	Haakonsen et al. (2004)
2003	102	117	Haakonsen et al. (2004)
2004	64	117	Aasestad (2006)
2005	51	161	Statistics Norway (2017)
2006	52	158	Statistics Norway (2017)
2007	51	146	Statistics Norway (2017)
2008	49	151	Statistics Norway (2011a)
2009	56	154	Statistics Norway (2011b)

The uncertainty on municipal level data for biofuels is high (Finstad et al., 2004). Data on a municipal level is estimated using national data. There is an uncertainty when national estimations of delivered energy are redistributed to regional shares. The consumption of biofuels is estimated from consumer services done by Statistics Norway and the consumption of oil from sales figures. Statistics Norway stopped publishing delivered energy data for non-electricity on the municipal level after 2009 as they viewed the uncertainty as to high.

Attempts were made to contact different companies known to have large market shares of the total sales of oil products used for heating in dwellings in Trondheim, but none were willing to provide sale statistics. Additionally, Norsk Petroleumsinstitutt was contacted, but they could not provide statistics on a municipal or regional level.

It seems unlikely that the delivered energy from biofuels in 1991 and 1995 could be on the level of 30-50 GWh considering that the national biofuels share of delivered energy to dwellings found by Sandberg et al. (2016) is much higher for the period. It has been assumed that the Trondheim share of biofuels and oil in the energy mix follows the national average before 1980 estimated by Sandberg et al. (2016). The energy mix is then calibrated towards the available Trondheim data of delivered energy from 1980 to present day.

3.3.7 Energy use per energy carrier and household

Statistics from 2009 and 2012 showing average energy use per energy carrier per household for Oslo and Sør Trøndelag was provided by Statistics Norway (2017) and is given in Table 15.

Table 15: Average energy use per household after region, energy carrier and time (Statistics Norway, 2017).

Year	Oslo				Sør Trøndelag			
	Electricity [GWh] (%)	Oil and paraffin [GWh] (%)	Firewood, pellets [GWh] (%)	Gas and district heating [GWh] (%)	Electricity [GWh] (%)	Oil and paraffin [GWh] (%)	Firewood, pellets [GWh] (%)	Gas and district heating [GWh] (%)
2009	11740 (80,9%)	1324 (9,1%)	866 (6,0%)	583 (4,0%)	16568 (79,5%)	333 (1,6%)	3797 (18,2%)	149 (0,7%)
2012	10420 (82,9%)	687 (5,5%)	620 (4,9%)	837 (6,7%)	14897 (76,3%)	383 (2,0%)	3558 (18,2%)	684 (3,5%)

The statistics presented in Table 15 has been used to estimate how much an increase in the district heating share will lead to a decrease in the delivered energy from other energy carriers.

3.4 Scenarios

For the future development of delivered energy to the Trondheim dwelling stock a scenario analysis has been performed. The baseline scenario assumes a "business as usual" trend from present day to 2050. From the baseline scenario, several variants considering different energy efficiency measures has been developed. An overview of the conceptual outline of the future scenarios is given in Figure 24.

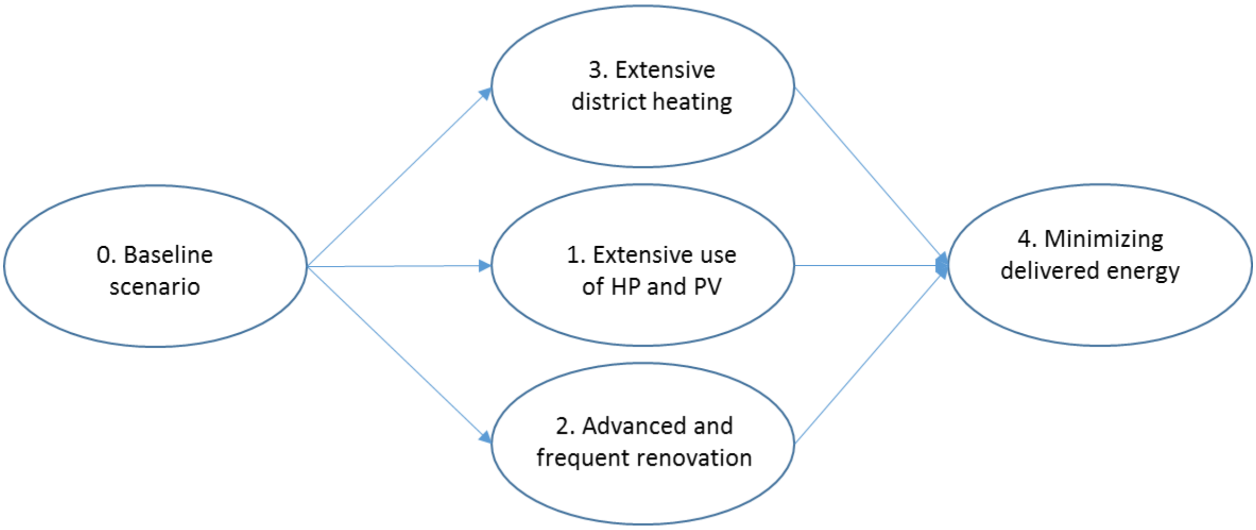


Figure 24: Conceptual outline of the scenario analysis for Trondheim Municipality. The lines between the scenarios indicate how the scenarios build on each other.

The baseline scenario can be considered the business as usual scenario. The other scenarios build on each other and include either a change from the baseline scenario (scenario 1-3) or a combination of changes (scenario 4). An outline overview of the given variants is given in Table 16.

Table 16: An overview of the different variant specifications used for the different scenarios.

	Variant 1		**Variant 2**	
	Description	*Applicable in scenario*	*Description*	*Applicable in scenario*
Renovation	Renovation cycle 40 years. Business as usual energy performance in renovated buildings.	0, 1, 3	Renovation cycle 30 years. Energy need intensity decreased for renovated dwellings and new construction giving lower energy intensities.	2, 4
Energy efficiencies	Baseline system efficiencies, PV and HP shares.	0, 2, 3	Increased system efficiencies.	1, 4
PV and HP shares	Baseline PV and HP shares.	0, 2, 3	Increased PV and HP shares. Increased COP for HPs.	1, 4
Energy mix	Baseline energy mix	0, 1, 2	District heating share increased. 75% share of all new compact dwelling energy mix after 2020.	3, 4

3.4.1 Baseline scenario

The baseline scenario can be considered as the business as usual scenario. Renovation trends and energy mix development is considered to continue as present. A model with 9 cohorts and 3 archetypes is used as used by Sandberg et al. (2016).

The stock model use the baseline population and person per dwelling input given in chapter 3.4. A renovation cycle of 40 years is assumed which is in line with Sandberg et al. (2016). The share of detached dwellings being distributed to SFH and TH is calculated based on the given data previously presented in Table 10. Average heated floor area per dwelling are given for the different segments and cohorts in Table 17. Energy need is then calculated based on the baseline energy need intensities input presented in Tabell 18 and Table 19 below.

Table 17: Average heated floor area [m2] per segment and cohort for the baseline scenario.

Average heated floor area [m2]			
Cohort	**SFH**	**TH**	**MFH**
0	133	88	56
1	133	88	56
2	139	101	53
3	144	100	61
4	161	96	64
5	139	85	58
6	142	88	60
7	152	96	68
8	152	96	68

Tabell 18: Energy need intensities for the baseline scenario for detached dwellings [kWh/m^2].

	SFH [kWh/m^2]			TH [kWh/m^2]		
Cohort	**Archetype 1**	**Archetype 2**	**Archetype 3**	**Archetype 1**	**Archetype 2**	**Archetype 3**
Cohort	256	149	149	238	140	140
0	256	149	149	238	140	140
1	182	130	130	178	128	128
2	161	123	123	160	123	123
3	143	118	118	141	116	116
4	147	120	120	142	116	116
5	89	73	73	88	71	71
6	63	35	35	65	36	36
7	35	35	35	35	35	35

Table 19: Energy need intensities for the baseline scenario for compact dwellings [kWh/m^2].

	MFH [kWh/m^2]		
Cohort	**Archetype 1**	**Archetype 2**	**Archetype 3**
0	197	139	139
1	197	139	139
2	205	121	121
3	126	100	100
4	115	102	102
5	118	101	101
6	81	71	71
7	63	32	32
8	38	38	38

The share of dwellings having heat pumps for the different segments is assumed to follow national estimations made by Sandberg et al. (2017). The assumed share of dwellings having installed heat pumps for the baseline scenario is given in Figure 25. Sandberg et al. (2017) weights the average COP of heat pumps to 2.6 for SFH and TH and 2.9 for MFH and assumes a continuation of trends towards 2050 for COP values. This results in an increase of the share of the energy need to heating and hot water being covered by HP from about 40% in in 2015 to 60% in 2050 for the total national dwelling stock. The same assumptions are used for the Trondheim baseline scenario.

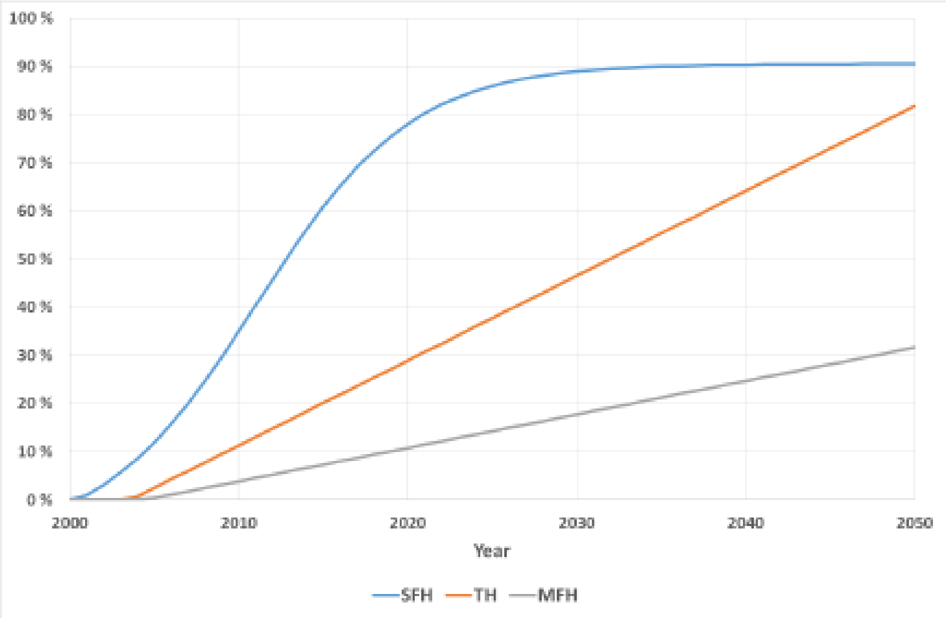


Figure 25: Baseline assumptions: shares having heat pump installed in the various dwelling types (Sandberg et al., 2017)

It is assumed an increase of dwellings having PVs from 0% in 2020 to 20% in 2050. PV intensities [kWh/m^2] by segments is given in Table 20.

Table 20:Baseline PV intensities [kWh/m^2] for different segments and cohorts.

Cohort	SFH [kWh/m^2]	TH [kWh/m^2]	MFH [kWh/m^2]
0	-28	-28	-14
1	-28	-28	-14
2	-28	-28	-14
3	-28	-28	-14
4	-37	-28	-14
5	-37	-28	-14
6	-37	-28	-14
7	-28	-28	-14
8	-28	-28	-14

Energy mix assumptions has been made and calibrated based on the statistics presented previously in chapter 3.4. The energy mix used in the model is segment-specific and time-dependent. The baseline 2016 energy mix and system efficiencies used to cover the energy need for heating and hot water that is not supplied by local energy sources is presented in Table 21. Assumed baseline 2050 values are presented in Table 22. For 2050 it has been assumed that oil will be phased out in 2020 which is in line with national policy goals. The share of district heating is assumed to increase as predicted by Statkraft (2017b). The share of biofuels is expected to remain constant and electricity is expected to cover the rest of the energy need. Assumed system efficiencies are the same as assumptions done by Sandberg et al. (2017) for the national level.

Table 21: Assumed baseline 2016 energy mix (heating and hot water) and weighted average system efficiency for groups of segment.

	Year	**2016**								
	Dwelling type	**SFH**			**TH**			**MFH**		
	Cohorts	**0-3**	**4-5**	**6-8**	**0-3**	**4-5**	**6-8**	**0-3**	**4-5**	**6-8**
Share energy carrier (%)	**El**	83	82	84	76	78	71	62	60	55
	Bio	11	11	11	11	11	11	5	5	5
	Oil	3	3	0	3	3	0	3	3	0
	District heating	3	4	5	10	10	15	30	35	40
Weighted average system efficiency		*0.89*	*0.89*	*0.91*	*0.93*	*0.94*	*0.95*	*0.93*	*0.96*	*0.96*

Table 22: Assumed baseline 2050 energy mix (heating and hot water) and weighted average system efficiency for groups of segment.

	Year	**2050**								
	Dwelling type	**SFH**			**TH**			**MFH**		
	Cohorts	**0-3**	**4-5**	**6-8**	**0-3**	**4-5**	**6-8**	**0-3**	**4-5**	**6-8**
Share energy carrier (%)	**El**	85	84	84	79	77	69	65	55	55
	Bio	11	11	11	11	11	11	5	5	5
	Oil	0	0	0	0	0	0	0	0	0
	District heating	4	5	5	10	12	20	30	40	40
Weighted average system efficiency		*0.94*	*0.94*	*0.95*	*0.96*	*0.97*	*0.97*	*0.96*	*0.97*	*0.97*

3.4.2 Scenario 1: Extensive use of HP and PV

The extensive HP and PV scenario is built on the baseline scenario. However, a faster and larger increase of dwellings having installed heat pumps and photovoltaics is assumed. The same assumptions for HP and PV shares are made for the Trondheim case as for the modelled national case by Sandberg et al. (2017). Heat pump shares for SFH dwellings is assumed to be equal to the baseline, but it is assumed a larger share of waterborne HPs which gives a higher COP. This is modelled as a linear increase in COP from 2.6 in 2016 to 3.0 in 2050 for SFH dwellings. For TH dwellings, a faster increase of HP share is assumed together with a larger share of waterborne HPs giving an increase in COP from 2.5 in 2015 to 3.0 in 2050. MFH dwellings are also assumed to have an increase in HP shares up to 60% in 2050 and a COP increase from 2.9 in 2016 to 3.1 in 2050 due to waterborne HPs.

These measures will give an increase in the total share of Trondheim dwellings having installed HPs from 40% in 2016 to 80% in 2050. The assumed heat pump shares for different segments in the extensive use of HP and PV scenario is given in Figure 26.

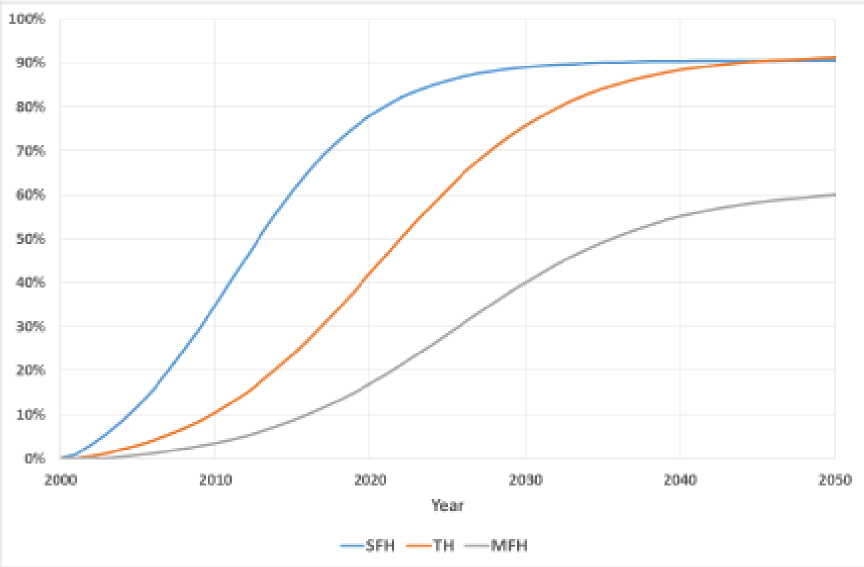


Figure 26: Extensive use of local energy sources: Shares having heatp pumps installed in the various dwelling types (Sandberg et al., 2016).

In this scenario, a broad implementation of PVs to dwellings is assumed from 2020. For cohorts 0-7 the PV share is assumed to reach 90% in 2050. For cohort 8 it is assumed that all dwellings will have PVs installed. The assumed share of dwellings having PV installed for the extensive PV scenario is given in Figure 27.

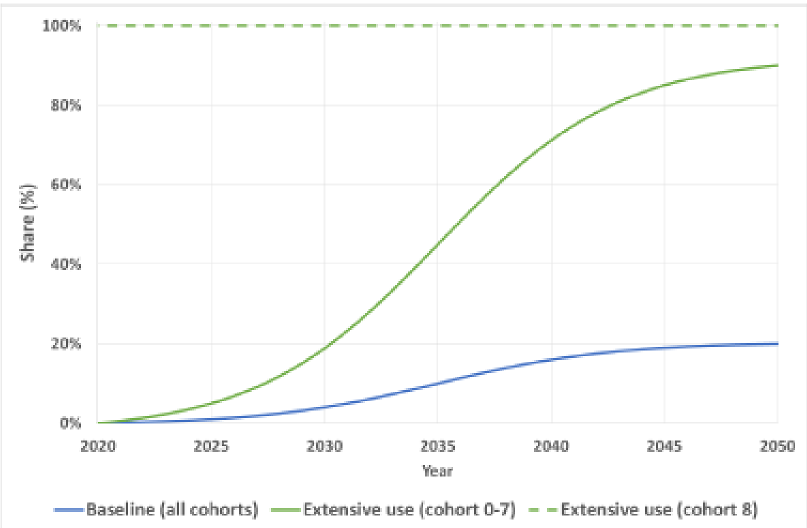


Figure 27: Shares of all dwellings having PV installed. Baseline and extensive use scenarios (Sandberg et al., 2016).

3.4.3 Scenario 2: Advanced and frequent renovation

To check the potential for future reductions in delivered energy to the dwelling stock by implementing renovation policies a scenario for advanced and frequent renovation has been created. A renovation cycle of 30 years is used together with improved energy intensity assumptions for different segment cohorts and archetypes. Energy intensities for the advanced renovation scenario is given in Table 23 and Table 24.

Table 23: Energy intensities[kWh/m^2] for heating and hot water for detached dwellings in the advanced renovation scenario.

	Single Family houses			Terraced Houses		
Cohort	**Archetype 1**	**Archetype 2**	**Archetype 3**	**Archetype 1**	**Archetype 2**	**Archetype 3**
0	256	149	65	238	140	60
1	256	149	65	238	140	60
2	182	130	64	178	128	62
3	161	123	62	160	123	62
4	143	118	65	141	116	62
5	147	120	71	142	116	67
6	89	73	61	88	71	60
7	63	35	38	65	36	39
8	35	35	35	35	35	35

Table 24: Energy intensities [kWh/m^2] for heating and hot water for MFH dwellings in the advanced renovation scenario.

	Multi Family Houses		
Cohort	**Archetype 1**	**Archetype 2**	**Archetype 3**
0	197	139	58
1	197	139	58
2	205	121	58
3	126	100	49
4	115	102	51
5	118	101	50
6	81	71	55
7	63	32	32
8	38	38	38

3.4.4 Scenario 3: Extensive use of district heating

The extensive use of district heating scenario builds on the baseline scenario and the input data are the same as in the baseline scenario except that the assumed future energy mix after 2020 is changed. In a scenario with broad implementation of district heating the main increase is expected to happen in MFH dwellings. However, a large increase towards 2050 is also assumed for SFH and TH dwellings. Mainly, the change of heating system is expected to happen when dwellings go through the renovation 40-year cycle and being moved to archetype 3. It has been assumed that the share of biofuels will remain constant towards 2050 for all segments and that an increase in the share of district heating will lead to a decrease in the share of electricity in the energy mix.

For SFH dwellings it is assumed that the share of district heating will remain around 3-5% towards 2050 for archetypes 1-2 in cohorts 0-7. For new construction after 2020 (cohort 8) it is assumed a share of 50% of delivered energy after HP contribution calculations to heating and hot water being from district heating. For archetype 3 it is assumed a district heating share of 50% for all cohorts. TH dwellings is assumed to have district heating shares between 10-20 for cohorts 0-7 in archetype 1-2. For cohort 8 in archetype 1 a share of 50% of district heating is assumed. In archetype 3 the same assumptions are made for TH as SFH that 50% of delivered energy demand to heating and hot water after HP contribution calculation is met by district heating. MFH dwellings in cohort 0-7 and archetype 1-2 is assumed to have a district heating share of 30-40%. Dwellings in cohort 8 in archetype 1-2 is assumed to reach a 75% share of district heating in the mix. For archetype 3 it has been assumed a 75% share of district heating for all cohorts. It has been assumed unlikely that MFH cohort 8 can reach a 100% share of district heating in the mix with the baseline HP share for MFH assumptions as HPs needs electricity to run corresponding with their COP and energy delivered. Therefore, the assumption of a 75% share was picked which still allows HPs to contribute to the energy demand to heating and hot water. An overview of the assumed 2050 energy mix to heating and hot water and system efficiencies is given in Table 25.

Table 25: Assumed 2050 energy mix (heating and hot water) and weighted average system efficiency for groups of segment for the extensive use of district heating scenario.

		Year	**2050**											
		Dwelling type	**SFH**				**TH**				**MFH**			
Archetype		**Cohorts**	**0-3**	**4-5**	**6-7**	**8**	**0-3**	**4-5**	**6-7**	**8**	**0-3**	**4-5**	**6-7**	**08**
1 & 2	**Share energy carrier (%)**	**El**	86	84	84	39	79	77	69	39	65	55	55	20
		Bio	11	11	11	11	11	11	11	11	5	5	5	5
		Oil	0	0	0	0	0	0	0	0	0	0	0	0
		District heating	3	5	5	50	10	12	20	50	30	40	40	75
3		**El**	39	39	39	39	39	39	39	39	20	20	20	20
		Bio	11	11	11	11	11	11	11	11	5	5	5	5
		Oil	0	0	0	0	0	0	0	0	0	0	0	0
		District heating	50	50	50	50	50	50	50	50	75	75	75	75
Weighted average system efficiency			*0.94*	*0.94*	*0.95*	*0.95*	*0.96*	*0.97*	*0.97*	*0.97*	*0.96*	*0.97*	*0.97*	*0.97*

3.4.5 Scenario 4: Minimized delivered energy

The minimized delivered energy scenario contains all considered energy efficiency measures and aims at assessing the possible reduction of delivered energy to dwellings in Trondheim Municipality towards 2050. It builds on the baseline scenario and implements a combination of all the previous scenarios.

For the minimized delivered energy scenario, the assumed HP and PV shares and system efficiencies are the same as in the extensive HP and PV scenario. Renovation rates are set to 30 years and energy intensities for different segments, cohorts and archetypes are assumed to be equal to the assumptions in the advanced and frequent renovation scenario. The energy mix assumed is the same as in the extensive district heating scenario.

3.5 Heating degree days factor

To project the future development of heating degree days (HDD) official climate projections according to IPCC's RCP4.5 scenario. Predictions for future temperature corresponding with RCP 4.5 is shown in Figure 28 and has been provided by Norsk Klimasenter (2017).

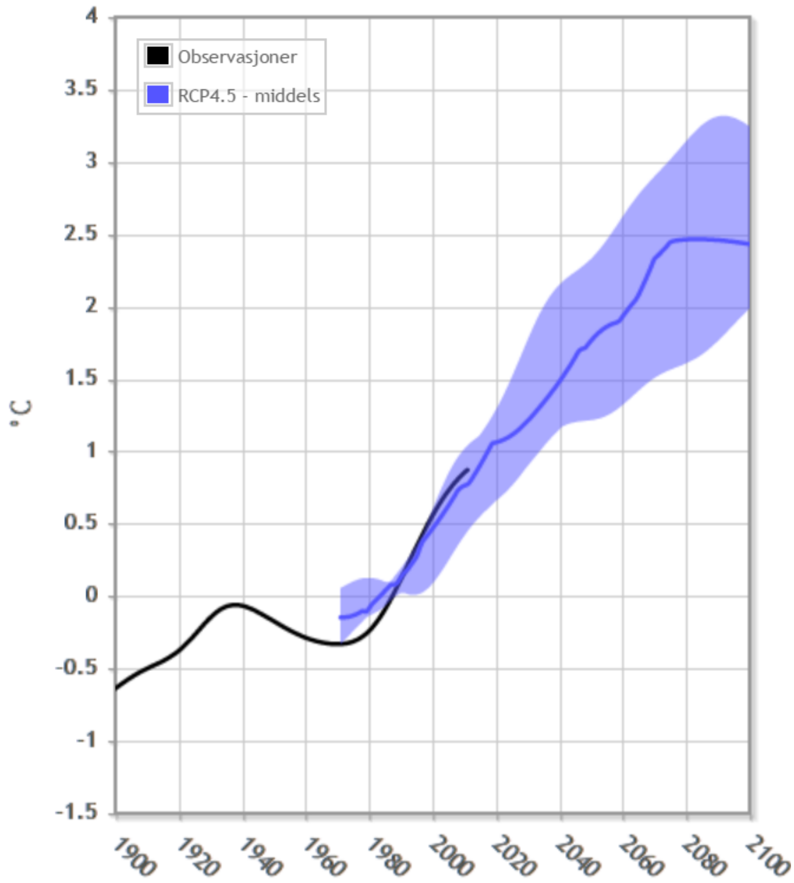


Figure 28: Showing average yearly temperature data and RCP4.5 temperature predictions for the Trøndelag area in the period 1900-2100 (Norsk klimasenter, 2017).

Based on the predictions presented in Figure 9 the future deviation from the 1971-2000 average for Trøndelag was estimated. Historical temperature data for 1960-2016 was provided by Norwegian Meteorological Institute (2017) and is presented in Figure 29. The location of the weather station has been relocated within Trondheim multiple times for the period 1960-2016. Due to the local temperature variations because of the location movements it was decided to only use data from the location with the most data available (Voll). A trendline for the deviation from the 1971-2000 mean was then calculated with an R^2 of 0.389.

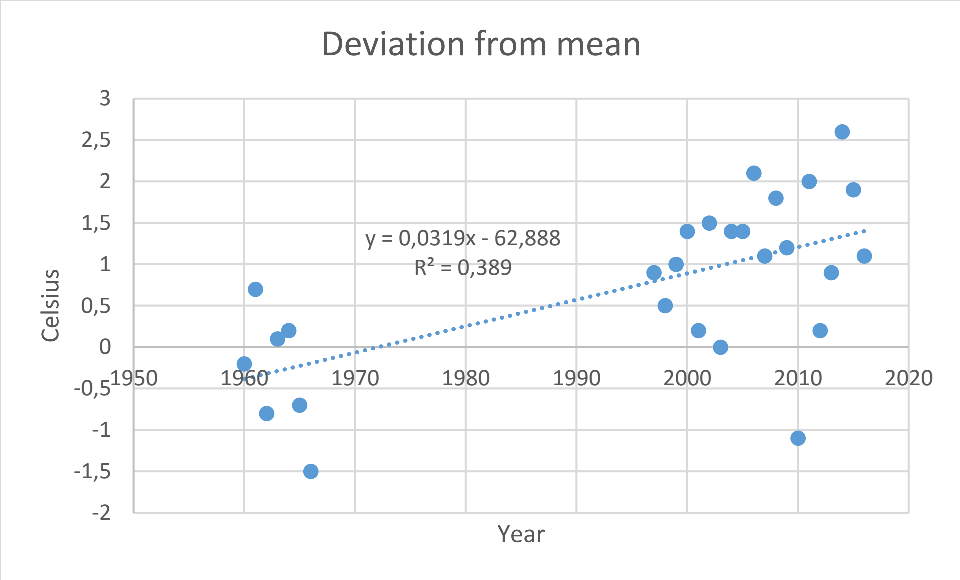


Figure 29: Historical deviation from mean (Norwegian Meteorological Institute, 2017).

Based on the gathered historical data and future RCP 4.5 projections the future heating degree days for each year was estimated and a HDD trendline was calculated as presented in Figure 30. This HDD trendline is then applied and multiplied to the model results.

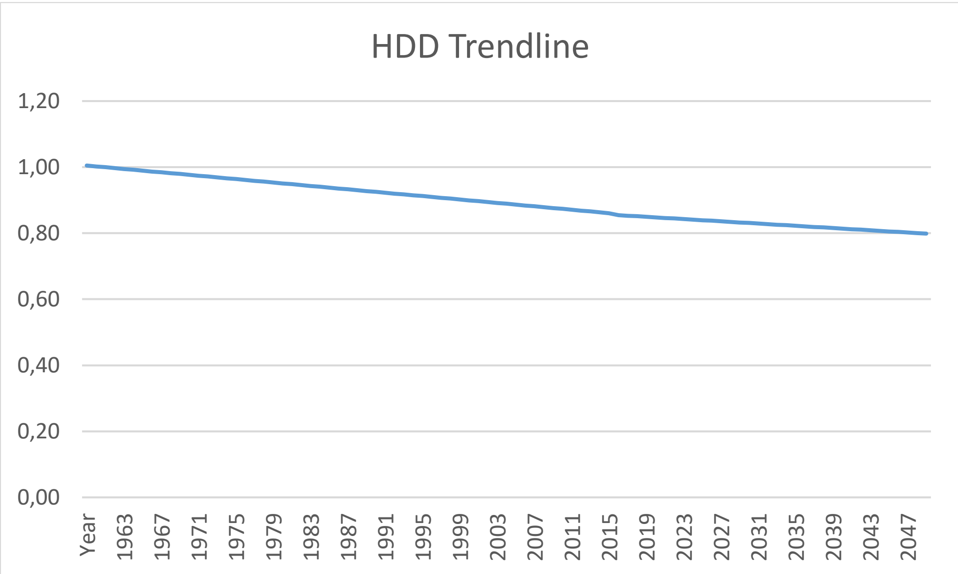


Figure 30: Estimated HDD correction factor for Trondheim.

3.6 Thermal adaption factor

Heating habits vary between dwellings of different energy state and the real energy demand for heating and hot water differs from the theoretical estimate over time (Sandberg et al., 2017) . Therefore, a thermal adaption factor is developed and applied to correct for the factors that creates this difference. The average divergence of real energy demand from the theoretical estimate is estimated using empirical data. For the case of Trondheim there are limited data available giving the total delivered energy to dwellings from all sources for given years. Only for the years 2004, 2005 and 2008 are total delivered energy given from statistics. The model is run both with the thermal adaption factor calculated by Sandberg et al. (2017) for the national level and a regional estimated adaption factor.

To estimate a regional thermal adaption factor (AF) for Trondheim Municipality trendlines has been estimated from the available data as given in Figure 31 . For the period 1960-1980 no data is available and estimations has been made corresponding to national statistics and included in the calculation. Estimated numbers are plotted in red. Trendlines are then added together giving an estimation of actual delivered energy per year from 1960-2016.

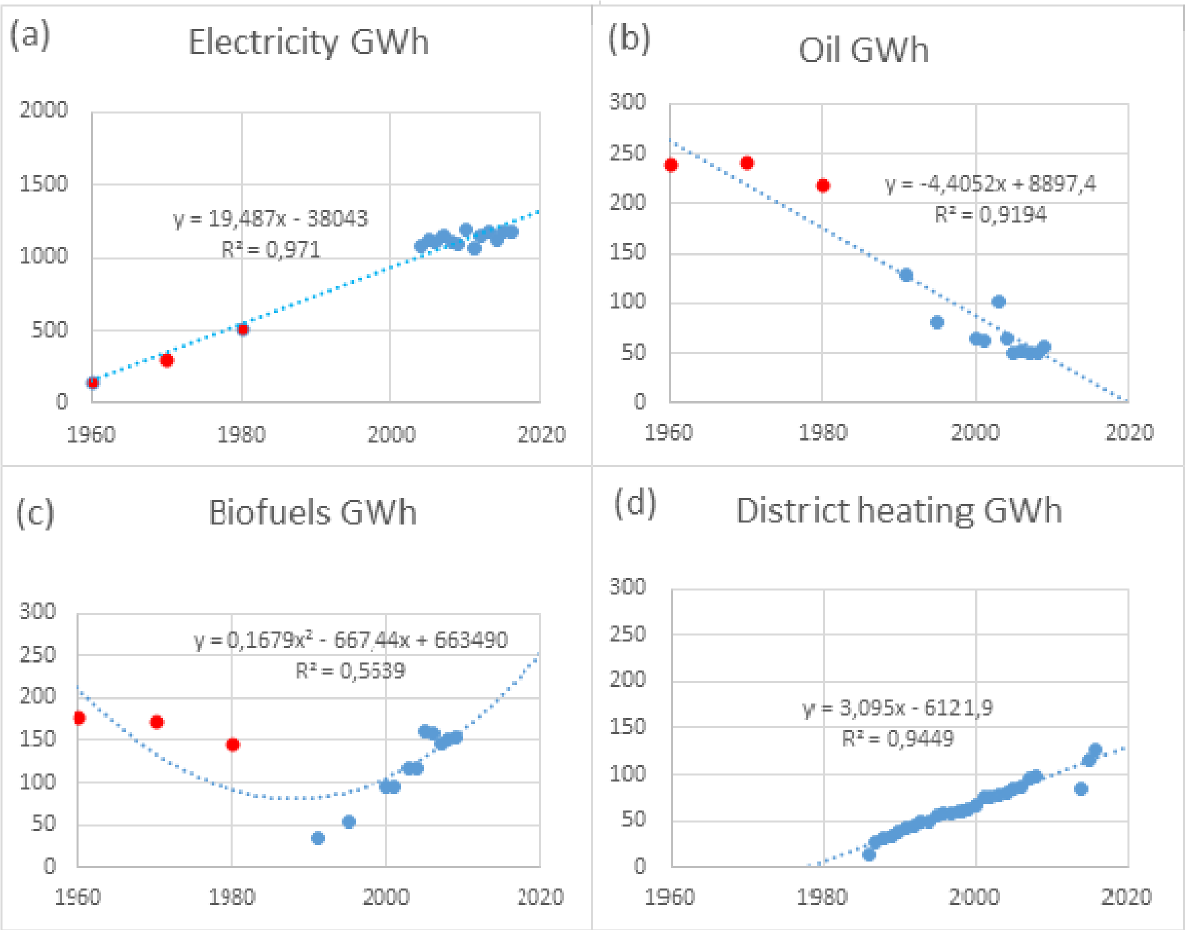


Figure 31: Plotted regression trends for delivered energy for electricity (a), oil (b), biofuels (c) and district heating (d). Red dots represents assumed values corresponding with national average energy mix shares as modelled by Sandberg et al. (2017) *and blue dots represents statistical data gathered for Trondheim. Note different y-axis!*

By using the summarized total delivered energy results from the trendlines of delivered energy for 1960-2016 from various sources an AF estimation for Trondheim Municipality has been calculated as presented in Figure 32. The 45 degree no adaption line represents a situation with no thermal adaption and a complete match between modelled theoretical results and actual data.

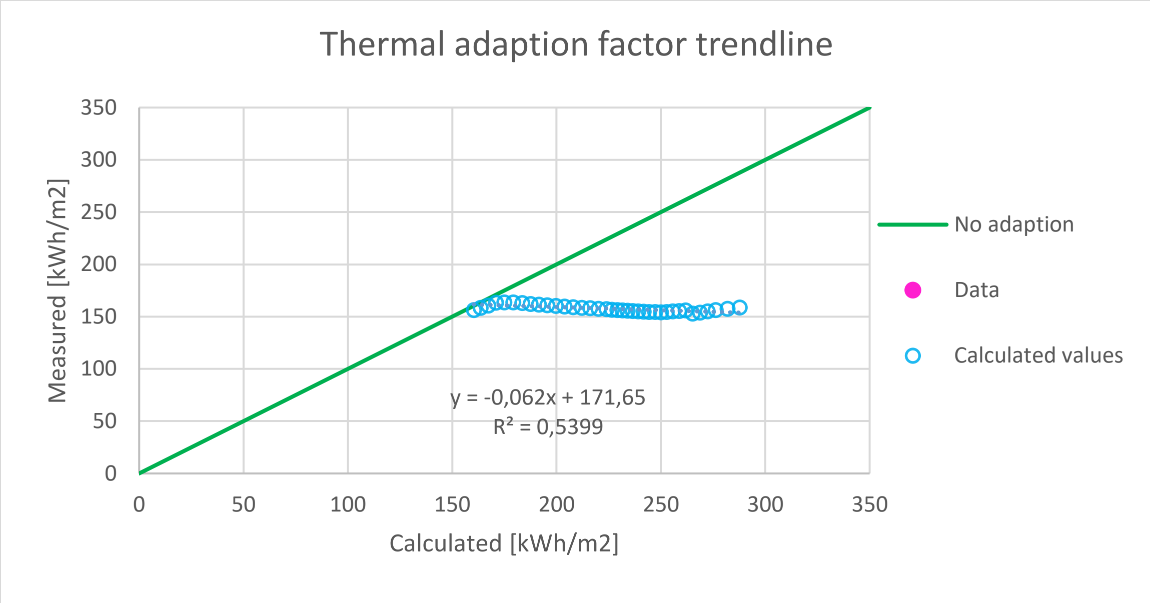


Figure 32:Thermal adaption factor trendline equation. Linear trendline from empirical observations for measured versus calculated energy use (current trends.)

The calculated trendline has a decreasing slope. This result is quite different from the slope estimated by Sandberg et al. (2017) on the national level and seems to be highly uncertain. Based on the trendline equation found the thermal adaption factor is calculated historically using model results and gathered data. The calculated Trondheim AF baseline factor is plotted with the National AF baseline factor in Figure 33.

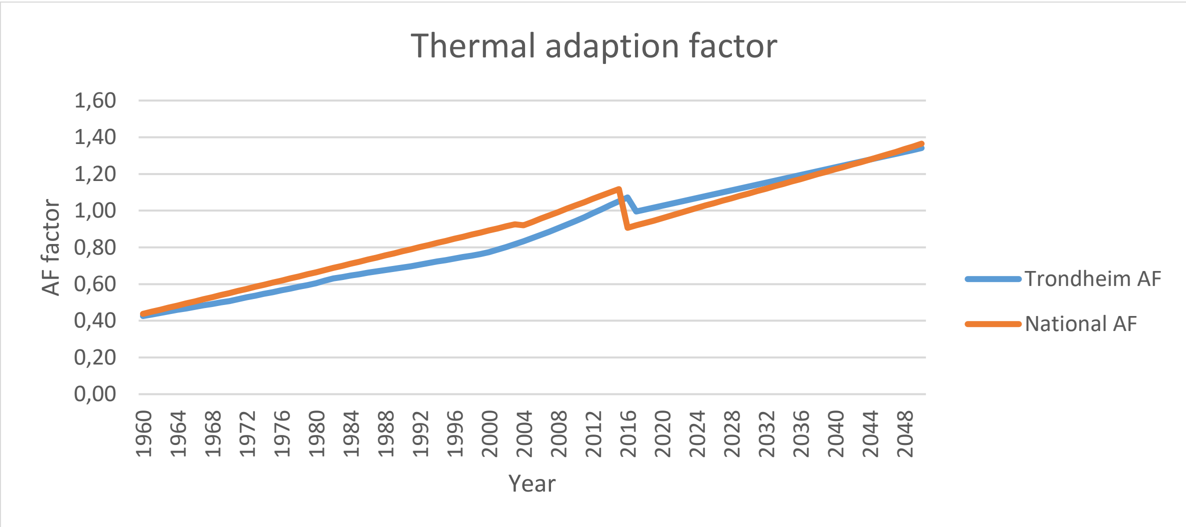


Figure 33:Estimated baseline thermal adaption factor for Trondheim and the Norwegian national average.

For the baseline scenarios the Trondheim and Norway AF factors seems to correlate and match quite well. However, problems were encountered when using the calculated Trondheim AF factor on other scenarios such as the minimized delivered energy scenario creating unrealistic results. For the historical delivered energy calculations the calculated Trondheim AF factor produced model results that were closer to statistical data than the Norway AF factor. Due to the uncertainty in the Trondheim future AF factor it was decided to use the national average AF trendline slope for the years 2017-2050. For the years 1960-2016 the Trondheim AF factor has been used in the model.

4 Results

4.1 Dwelling stock evolution

To estimate the future delivered energy to the Trondheim dwelling stock it is first necessary to model the future dwelling stock development. This is done by using the methodology described previously in chapter 3.4 and results are presented below. The model use the smoothed gathered population data, persons per dwelling data and medium population forecasts for Trondheim.

4.1.1 Dwelling stock size and composition

Model results giving the simulated Trondheim dwelling stock size is presented in Figure 34

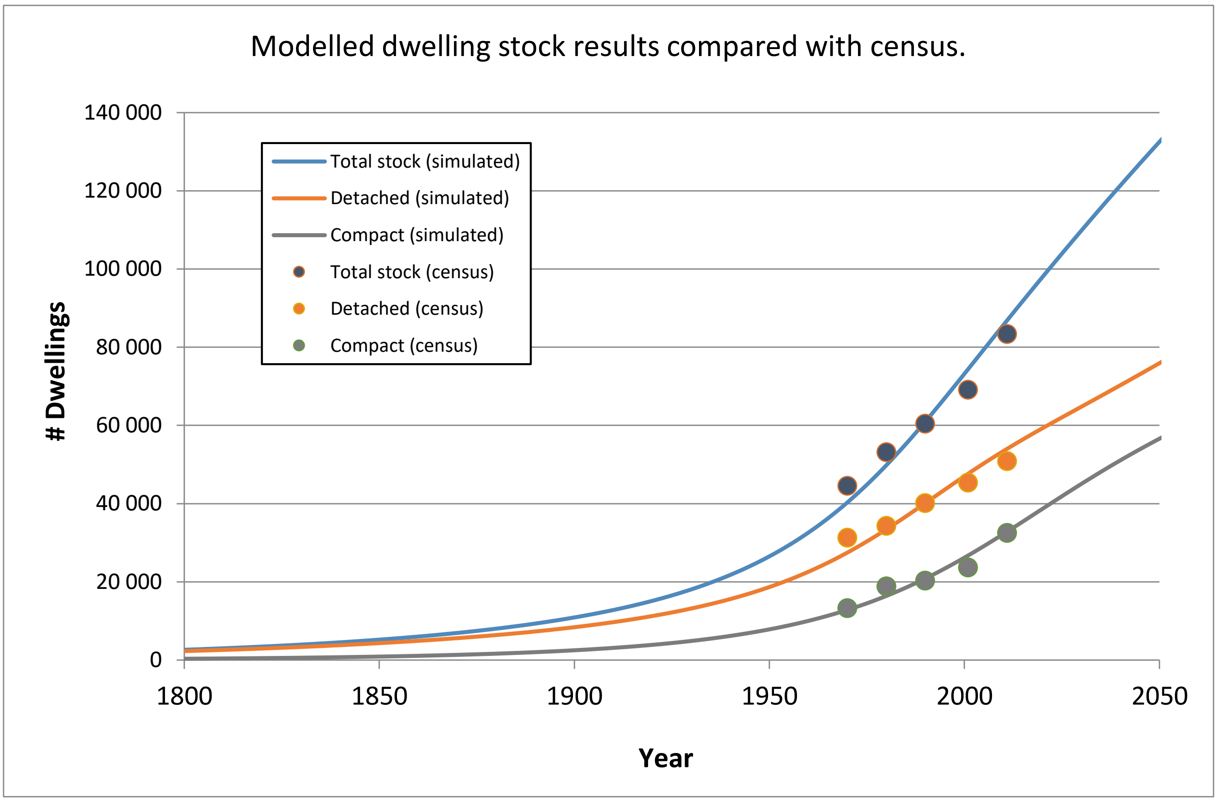


Figure 34: Comparing the simulated stock result with census from (Statistics Norway, 2016b).

The total dwelling stock is expected to increase towards 2050 for both detached and compact dwellings. The total stock is estimated to 133 000 in 2050 out of which it is estimated a total of 76 000 detached dwellings and 57 000 compact dwellings. The comparison seems to give a good fit between the total stock and the census stock data for the period 1970-2011. The dwelling stock is then segmented for the period 1960-2050 into SFH, TH and MFH dwellings. The 1960 stock is estimated to about 15000 TH, 10000 MFH and 8000 SFH dwellings. In 2016 the stock is modelled to about 35000 MFH, 30000 TH and 25000 SFH dwellings. Towards 2050 the MFH segment is expected to have to largest growth to about 65000 dwellings. For the detached dwellings, it is expected about 36000 SFH dwellings and 39000 TH dwellings. Results are presented in Figure 35.

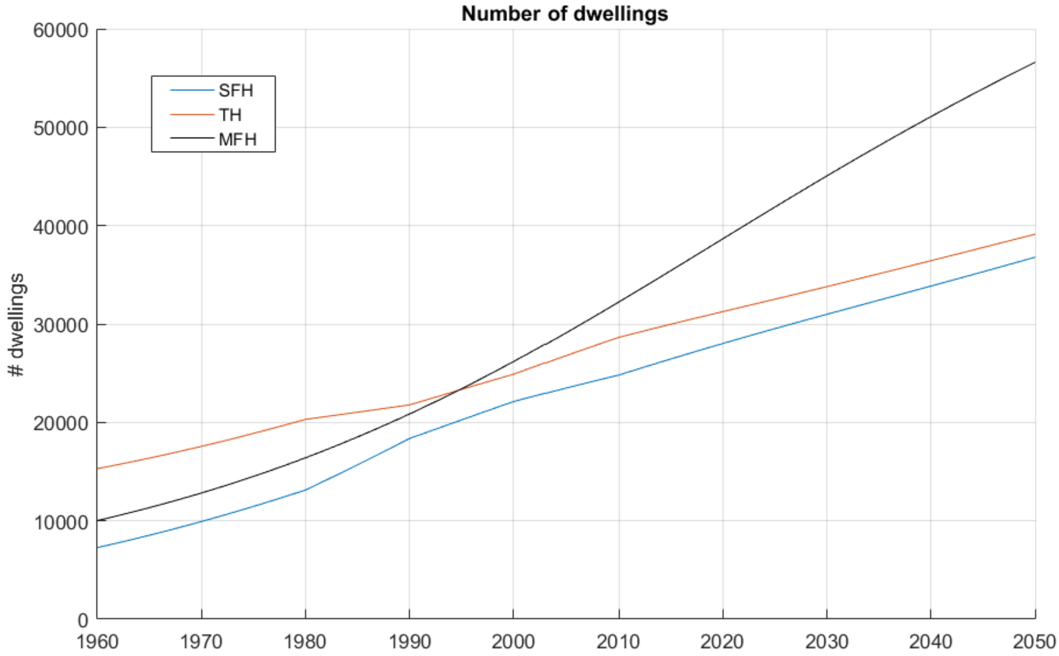


Figure 35: Modelled number of dwellings in stock for each segment for the period 1960-2050.

A comparison of the dwelling stock in Trondheim and the national level for selected European countries is presented in Figure 36. As stock size varies greatly over time and location each stock has been normalized corresponding to its 2016 size. It is worth noting that the results for the 2050 and 2016 simulation for Trondheim in Figure 36 (a) are calculated for different years than the statistical data and the national level in Figure 36 (b). Legends in the first row in Figure 36 (a) represents statistical data while legends in the second row represents model results. For Trondheim's dwelling stock a growth of about 35 % towards 2050 from present day is expected. It is difficult to compare the sub segments of the Trondheim dwelling stock share constructed before 1980 from statistical data with the simulated results due to the different distribution. Still it seems like the total share of dwellings constructed before 1955 for the 2016 simulation corresponds quite well with statistics from 2011 showing the dwellings constructed before 1946. The modelled 2050 results show the number of dwellings constructed before 1955 shrinking some compared to the modelled 2016 results. This is natural as older buildings gets demolished and new construction takes place. Strangely, the statistical data from 2011 indicates a larger number of dwellings constructed before 1980 than the data from 1980 itself. The reason for this has not been identified.

Comparing the results for Trondheim with results from the national level of some selected countries obtained by shows that the 2050 growth in Trondheim compared to present day of about 35% corresponds well with the Norwegian national expected stock growth. Both Trondheim and Norway is expected to have a larger stock growth than The Netherlands, Serbia and Slovenia. The share of the stock that belongs to both the given 1980-2020 and 2020-2050 cohort is modelled to become slightly larger in Trondheim than in the national Norwegian level's corresponding 1981-2015 and 2016-2050 cohorts. The share of older buildings constructed before 1980 is expected to be smaller in Trondheim than the Norwegian level.

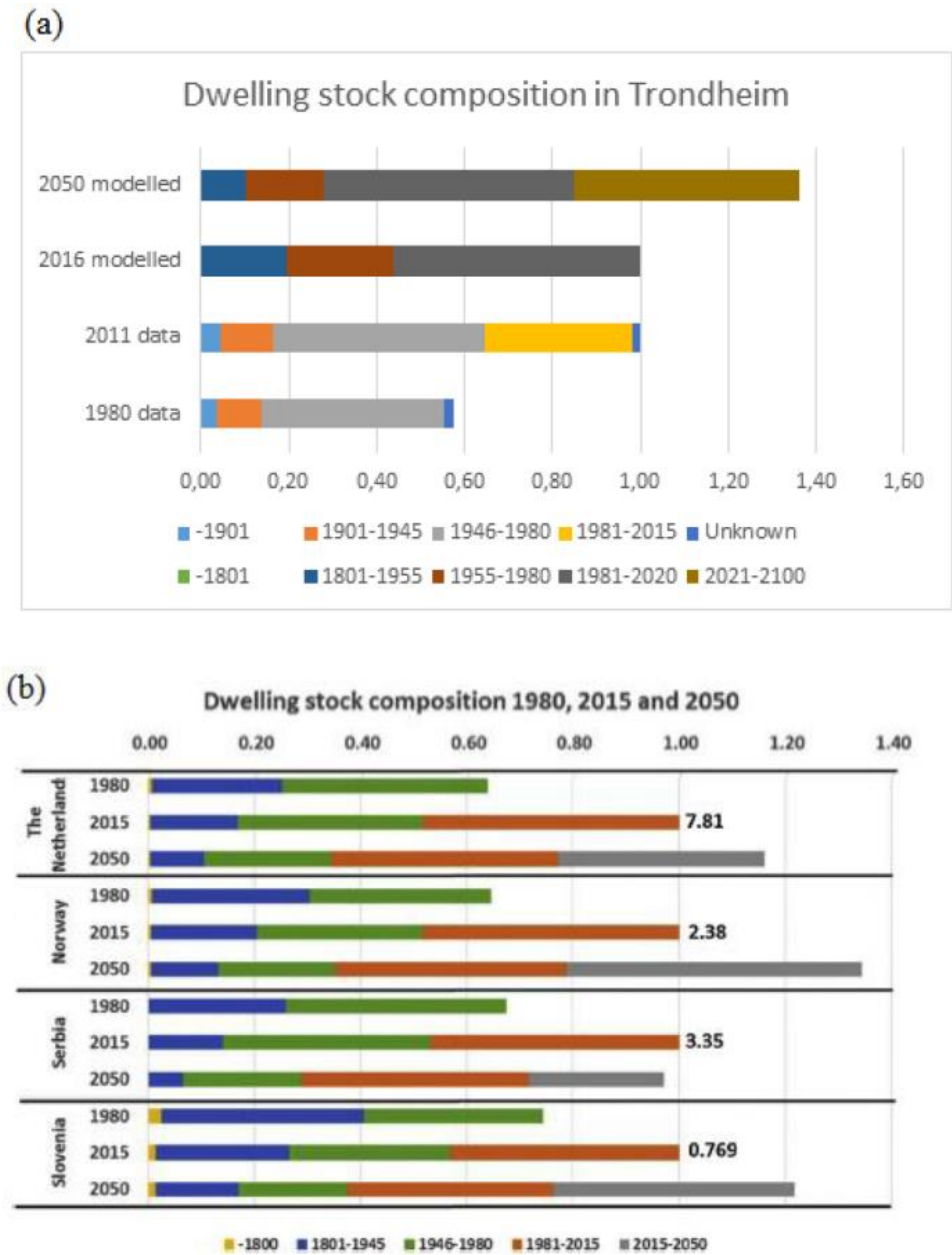


Figure 36: Normalized dwelling stock compositions for different cohorts for (a) Trondheim and (b) the national level in selected countries from Sandberg et al. (2016).

4.1.2 Construction, demolition and renovation activity

The modelling results using collected and smoothed population data, persons per dwelling data and medium population forecast for Trondheim is given in Figure 37.

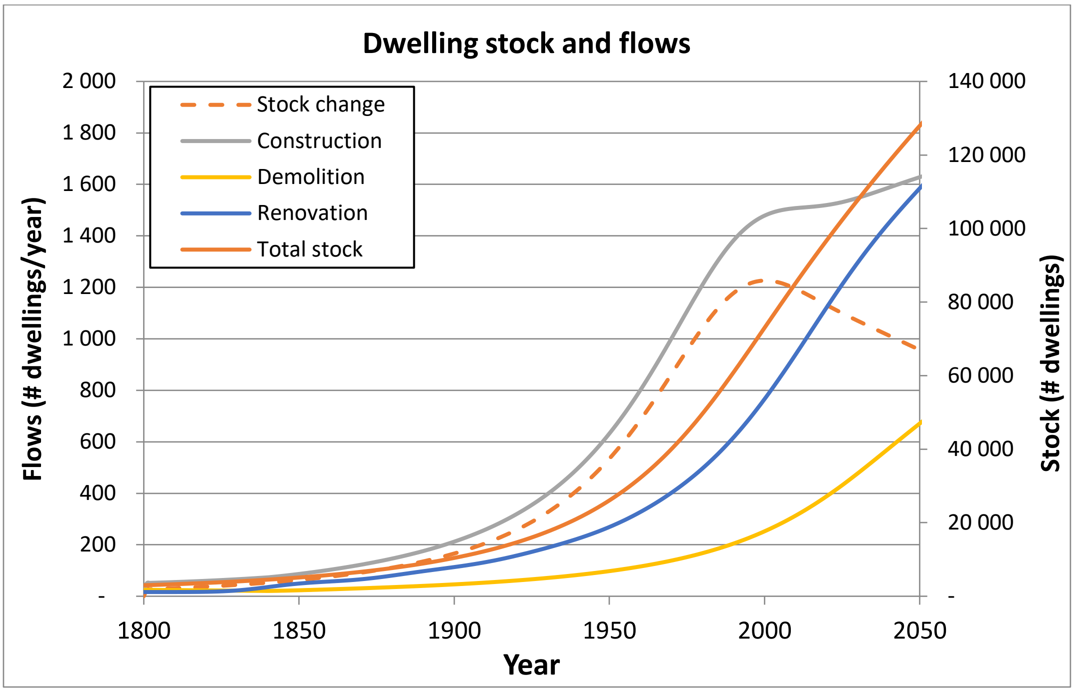


Figure 37: Dwelling stocks and flows in Trondheim modelled towards 2050 for the baseline scenario.

While the dwelling stock is expected to increase towards 2050 the modelled results show that the pace of dwellings per year being added to the stock is expected to decrease from present day to 2050. Still construction activity is expected to increase slightly, but this is countered by an increase in demolition activity. Renovation activity is also expected to increase from about 1000 dwellings per year at present to about 1600 dwellings per year in 2050.

A comparison of the simulated yearly construction in the period of 2008-2016 with statistical data has been performed and results are shown in Table 26.

Table 26: Simulated yearly construction for the years 2008-2016 and actual construction data provided by SSB (2016b).

Year	Simulated total	Constructed total	Simulated detached	Constructed detached	Simulated compact	Constructed compact
2008	1542	1828	835	576	707	1252
2009	1547	692	832	403	715	289
2010	1552	431	830	198	722	233
2011	1556	922	827	757	729	165
2012	1561	898	826	519	735	379
2013	1565	972	824	426	741	546
2014	1570	2109	823	1058	747	1051
2015	1574	1404	822	472	752	932
2016	1579	2081	822	985	757	1096
SUM	**14046**	**11337**	**7441**	**5394**	**6605**	**5943**

Now calculating the yearly average construction for the given years and doing error estimations of the simulated construction the results in Table 27 is obtained.

Table 27: Error estimation of simulated yearly construction compared to actual construction data provided by SSB (2016b) for the period of 2008-2016.

	Simulated total	**Constructed total**	**Simulated detached**	**Constructed detached**	**Simulated compact**	**Constructed compact**
Yearly Average construction	1561	1260	827	599	734	660
Error (%)	24 %	-	38%	-	11 %	-

This shows a large error estimation for the simulation of the period. The simulation of detached construction represents an error of 38% compared to statistics. An error of 11% for compact is estimated and in total the error is 20% These errors seems quite large and indicates an overestimation of new construction for the period.

4.2 Energy need in the Trondheim dwelling stock

The yearly energy need for the Trondheim dwelling stock has been calculated from the modelled dwelling stock floor area size, energy need intensities for space heating and assumed energy need for electrical appliances. Results are presented in Figure 38.

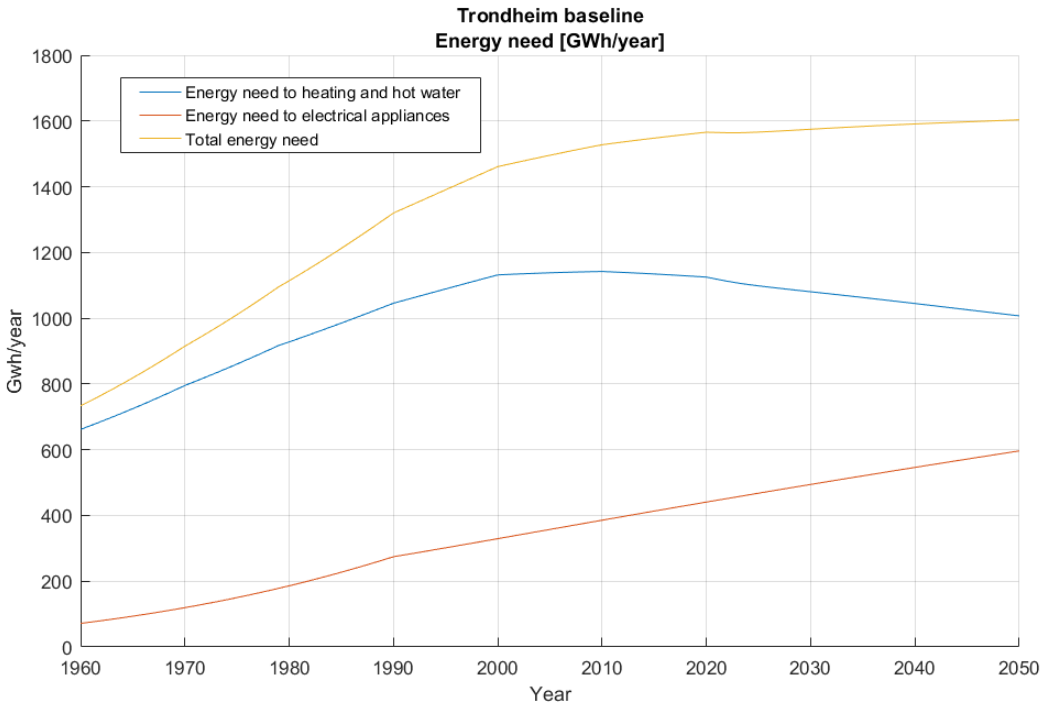


Figure 38:Modelled energy need for the Trondheim dwelling stock for the years 1960-2050.

Figure 38 shows the calculated technical estimated energy need for Trondheim with energy need to electrical appliances in red and energy need to heating and hot water in blue. The sum of the red and blue line equals the total energy need in yellow. Estimated historical energy need to heating and hot water in Trondheim's dwelling stock has been increasing from about 700 GWh/year in 1960 to about 1100 GWh/year in 2000 before remaining quite stable towards 2016. Towards 2050 the energy need to heating and hot water is expected to decrease slightly from about 1100 GWh to 1000GWh despite the expected increased size of the dwelling stock. Energy need to electrical appliances has been historically modelled to been increasing steadily for the whole period 1960-2016 from about 100 GWh/year to 400 GWh/year. In the future, it is expected to keep increasing to about 600GWh/year in 2050 which also match the expectations of an increased dwelling stock.

The historical development of total energy need in the stock is the sum of the energy need to heating and hot water and the energy need to electrical appliances. The total energy need is modelled to have been increasing from about 700GWh/year in 1960 to almost 1600 GWh/year in 2016. It is expected a slight increase in the total energy need towards 2050. Based on the energy need the delivered energy for the system is then calculated as described in the methodology chapter.

4.3 Baseline delivered energy results

The baseline scenario can be considered the business as usual scenario. It attempts to model the historical total delivered energy to the system as realistically as possible. Technical estimated results are corrected for HDD and AF factors to produce the estimated "real" scenario results. The estimated real delivered energy to Trondheim's dwelling stock for each energy carrier and with PV and HP contributions for the baseline scenario is presented in Figure 39.

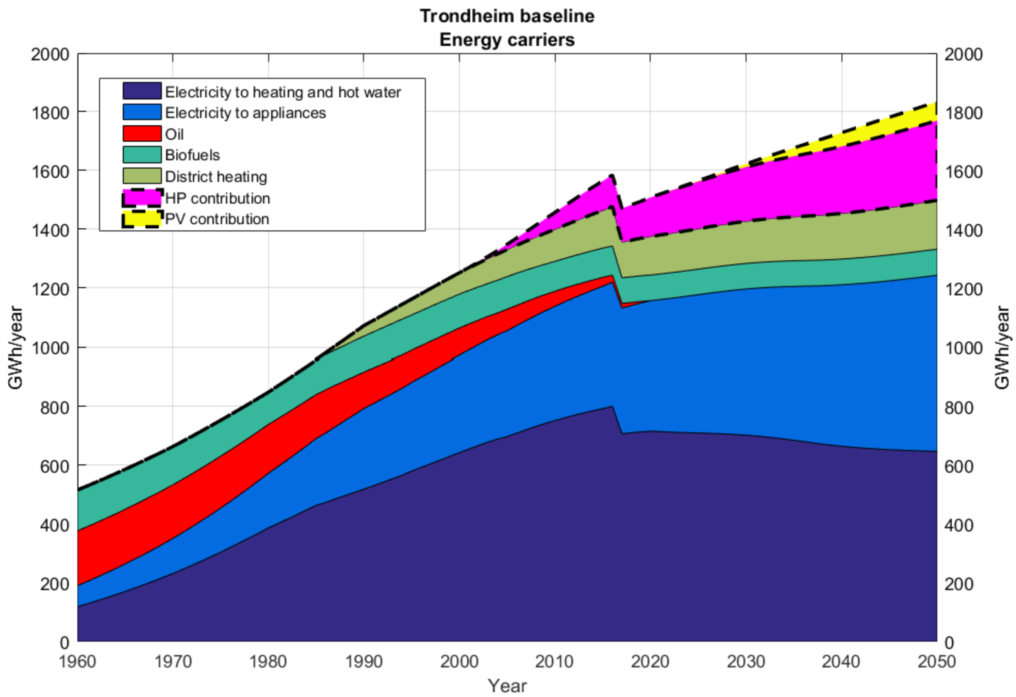


Figure 39: Calculated "real" delivered energy carriers including PV and HP contributions for the Trondheim baseline scenario.

Historically the model results points towards an increase from about 500 GWh per year delivered energy to dwellings in Trondheim in 1960 to about 1500 GWh per year at present day excluding HP and PV contribution. The results show that oil has been gradually phased out during the period while the biofuels share has decreased slightly. District heating entered the mix in 1986 and HPs started being implemented during the 2000s. Electricity has been gradually increasing its share in the energy mix. The large drop in estimated delivered energy in 2017 is due to the change from the calculated Trondheim AF factor to the national trendline.

Total estimated real delivered energy to the system is expected to be almost constant and grow very slightly from 1480 GWh per year at present to 1490 GWh per year in 2050. Electricity is expected to be the dominant energy carrier towards 2050. Electricity to heating and hot water is expected to drop from about 800 GWh per year at present day to about 650 GWh per year in 2050. Electricity to appliances is expected to increase in the period from about 400 GWh per year in 2016 to 600 GWh per year in 2050. Delivered energy from oil is expected to be phased out in 2020 in line with policy goals and biofuels is expected to remain about constant around 90 GWh per year from present day towards 2050. District heating is expected to increase from about 130 GWh per year at present to about 170 GWh per year in 2050 for the baseline scenario. A HP contribution of about 100 GWh at present is in 2050 expected to reach about 250GWh per year. PV contribution is expected to grow from zero at present to about 50 GWh per year in 2050.

4.4 Scenarios

Scenario results for modelled delivered energy for all Trondheim scenarios is given in Figure 40 and Figure 41. Delivered energy is expected to grow from 2016 to 2050 for the baseline scenario and the extensive district heating scenario. For the other scenarios, a decrease in delivered energy is expected in 2050. A change in the energy mix can be seen in the extensive district heating scenario and the minimized delivered energy scenario. Each scenario is discussed in detail in the subchapters 4.4.1-4.4.4.

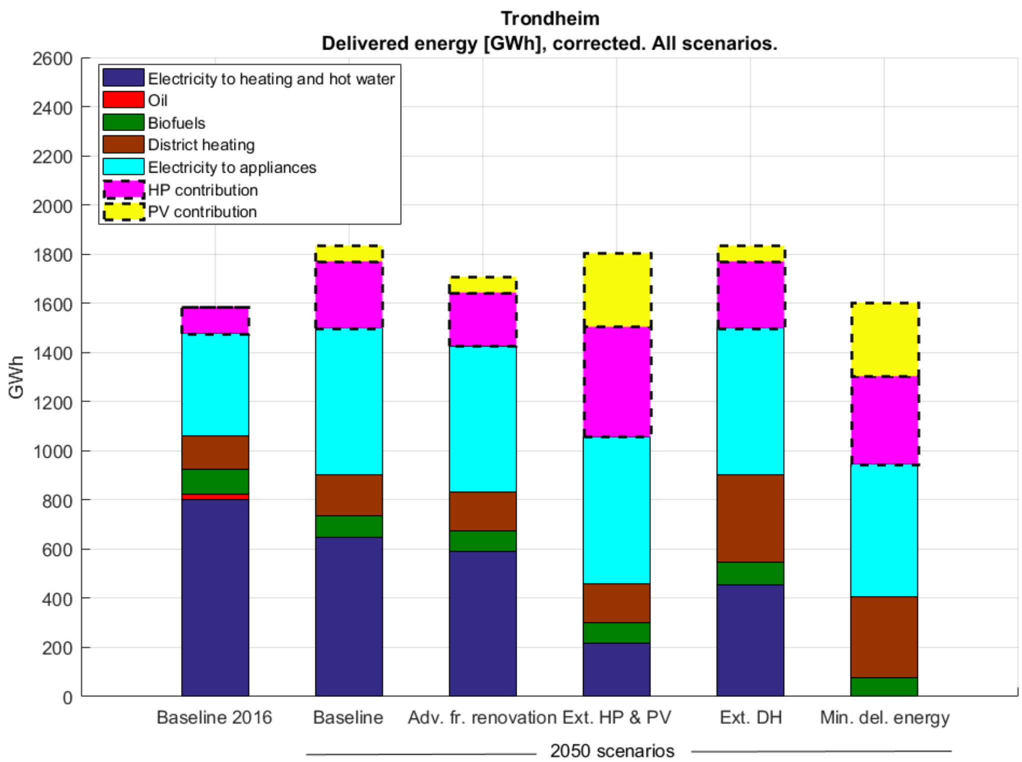


Figure 40: Total delivered energy and energy mix in 2016 and 2050 for all scenarios. Estimated total "real" delivered energy.

4.4.1 Scenario 1: Extensive PV and HP results

For the extensive use of heat pumps and photovoltaics scenario a large increase in electricity generated by photovoltaics and a large increase in the share of heat pumps in the dwelling stock is assumed. A large increase in the 2050 HP contribution to about 450 GWh per year and a PV contribution of 300 GWh per year is expected. This is expected to lead to a future decrease of about 30% in total delivered energy to the system. Compared to the business as usual scenario an extensive implementation of heat pumps and photovoltaics is expected to result in about 1050 GWh per year delivered energy to dwellings in 2050 while the baseline result is about 1500 GWh per year. Model results for the extensive PV and HP scenario is presented in Figure 41a.

4.4.2 Scenario 2: Advanced and frequent renovation

The advanced and frequent renovation scenario represents a faster movement of dwellings to archetype 3 and increased efficiencies in the system giving a lower heating demand per floor area. The 2050 model results for the advanced and frequent renovation scenario shows a decrease in the delivered energy to 1430 GWh per year to the system compared with the 1500 GWh per year baseline scenario results. This is a reduction of 5%. Scenario results with estimated delivered energy and carriers is presented in Figure 41b.

4.4.3 Scenario 3: Extensive District heating

The extensive district heating scenario represents a situation where policy measures are taken to increase the share of district heating in the dwelling stock energy mix. For this scenario, the energy demand, PV and HP contributions and system efficiencies are equal to the baseline. However, an increase in the delivered energy from district heating to the system from 130 GWh per year in 2016 to 330 GWh per year in 2050 is expected. This represents a share of 66% of the total delivered energy to heating and hot water in 2050 excluding PV and HP contribution. Scenario results with estimated delivered energy and carriers is presented in Figure 41c.

4.4.4 Scenario 4: Minimized delivered energy

The minimized delivered energy scenario is built on the baseline scenario with measures from all the other scenarios combined. Extensive PV and HP shares, an energy mix with extensive use of district heating and renovation cycles of 30 years and increased efficiency of renovated dwellings is assumed. Model results suggests that by combining all these measures a decrease of 37% in the delivered energy to the dwelling stock in 2050 compared to today is possible despite the expected growth of the dwelling stock. The total delivered energy to the system is expected to be about 950 GWh per year in 2050 out of which only 400 GWh per year is for heating and hot water. Note that PV contribution is modelled as a contribution to electricity to heating and hot water until the electricity delivered to heating and hot water reach zero in 2047. The surplus PV contribution after this is then modelled as a contribution to electricity to appliances. A large increase to 330 GWh per year in district heating is expected in 2050. HP contribution is expected to be about 360GWh per year in 2050 and a PV contribution of 300 GWh per year. The HP contribution is lower here than in the extensive HP and PV scenario as the total energy need is lower due to the advanced and frequent renovation policy as more dwellings are renovated to better energy efficiencies. Model results for the minimized delivered energy scenario is presented in Figure 41d.

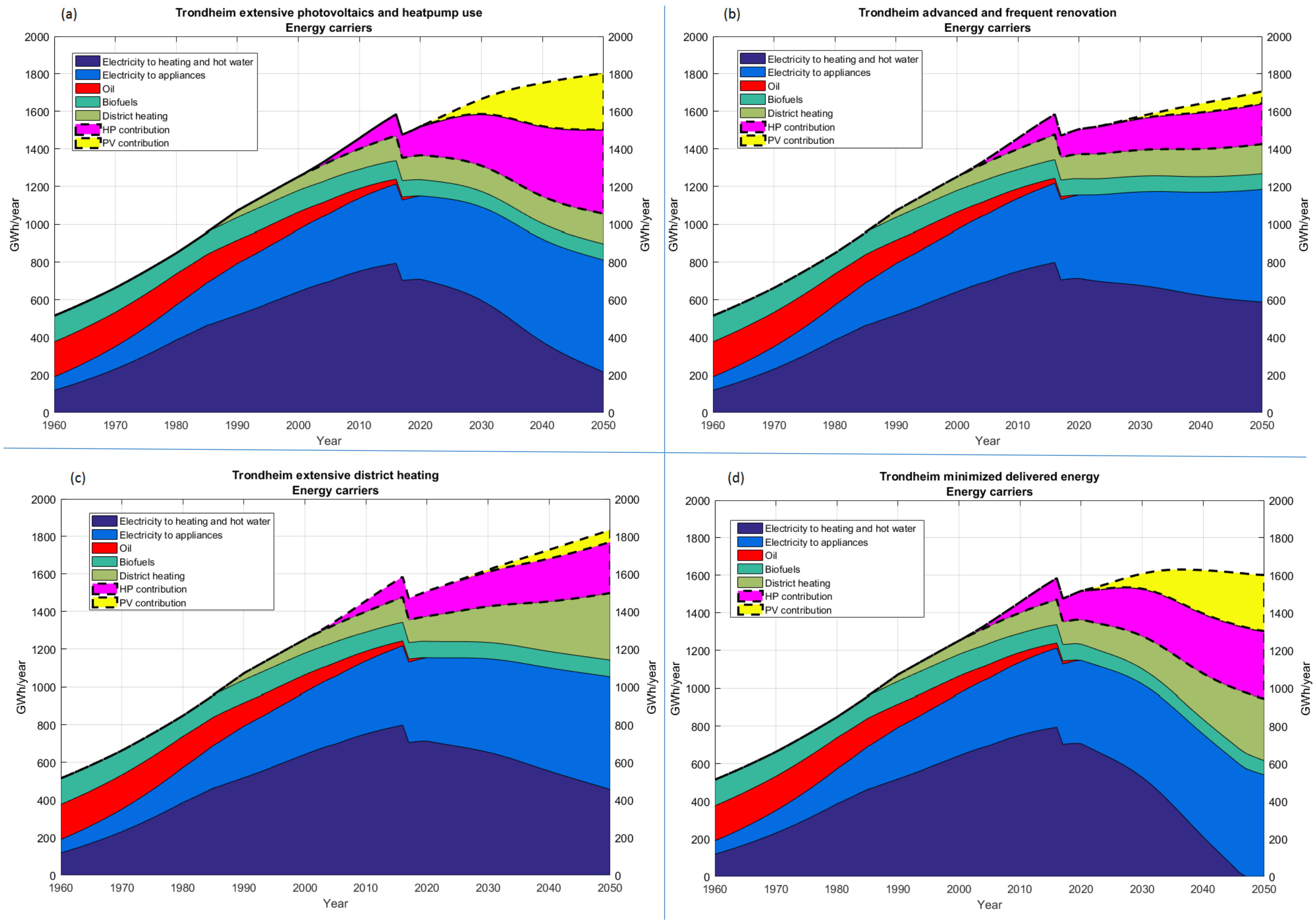


Figure 41: Calculated "real" delivered energy carriers [GWh/year] including PV and HP contributions for all Trondheim scenarios. (a): Scenario 1, Extensive PV and HP. (b): Scenario 2, advanced and frequent renovation. (c): Scenario 3, extensive district heating. (d): Scenario 4, minimized delivered energy.

4.5 Energy analysis

The results suggest that a broad use of local energy sources is the measure that is expected to have the largest potential to reduce total delivered energy to the dwelling stock in Trondheim. This is also considered to be a more cost efficient way of decreasing the total delivered energy (Sandberg et al., 2017). Advanced and more frequent renovation is also shown to have a potential for reducing the total delivered energy of the system, but the reduction is smaller than for the extensive PV and HP scenario. A broad implementation of district heating towards 2050 will not give any total delivered energy reduction, but will give a 250% increase in delivered energy from district heating compared to present day.

Estimations were also done to investigate how delivered energy to each cohort contribute to the total delivered energy in the system. The estimated delivered energy to each cohort for Trondheim's baseline scenario is presented in Figure 42.

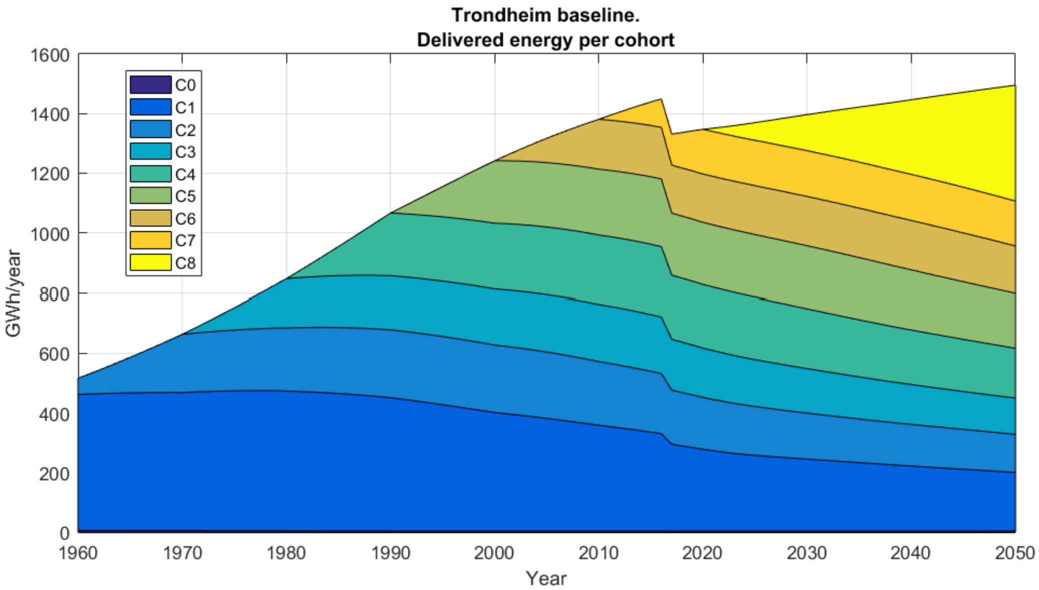


Figure 42: Estimated "real" yearly delivered energy per cohort for the Trondheim dwelling stock for the baseline scenario.

Figure 42 describes how the delivered energy to each cohort has developed over time. Historically delivered energy from cohort 1 has decreased from about 500 GWh per year to less than 350 GWh per year in 2016. This happens mainly due to increased energy efficiency after renovation and partly because of demolition of older buildings. Over time new construction happens and the newer cohorts appears and contributes to the total delivered energy. The future estimation shows that delivered energy to each of the pre-2010 cohorts is expected to decrease further towards 2050. A comparison of simulated delivered energy to different cohorts for the years 2016 and 2050 with the calculated change is presented in Table 28. The simulated results estimate the largest percentage of decrease in delivered energy to cohort 1. Cohort 6 is expected to have the smallest decrease percentage in delivered energy. This can be explained by the fact that cohort 1 has the largest energy intensity demand per floor area and therefore the largest potential for energy efficiency measures. Cohort 7 is expected to have an increase in delivered energy as dwellings are still being constructed in the cohort during years 2017-2020. Cohort 8 will have a gradually increase in delivered energy as new dwellings are being constructed towards 2050. In total an increase in total delivered energy of 3% is expected for the whole stock from 2016 to 2050.

Table 28: Estimated "real" yearly delivered energy per cohort for the years 2016 and 2050 and the expected change in the period.

	Delivered energy to specific cohorts, GWh per year.									
Year	Cohort 0	Cohort 1	Cohort 2	Cohort 3	Cohort 4	Cohort 5	Cohort 6	Cohort 7	Cohort 8	Sum
2016	4.02	326	202	189	233	227	173	95.3	0	1449
2050	3.80	196	127	121	167	181	158	150	388	1492
Change (%)	-6 %	-66 %	-59 %	-56 %	-40 %	-25 %	-9 %	36 %	n/a	3%

To investigate how different considered measures and possible scenarios will affect the delivered energy intensity per floor area over time the delivered energy kWh per m^2 was calculated. Results for all scenarios are shown in Figure 43.

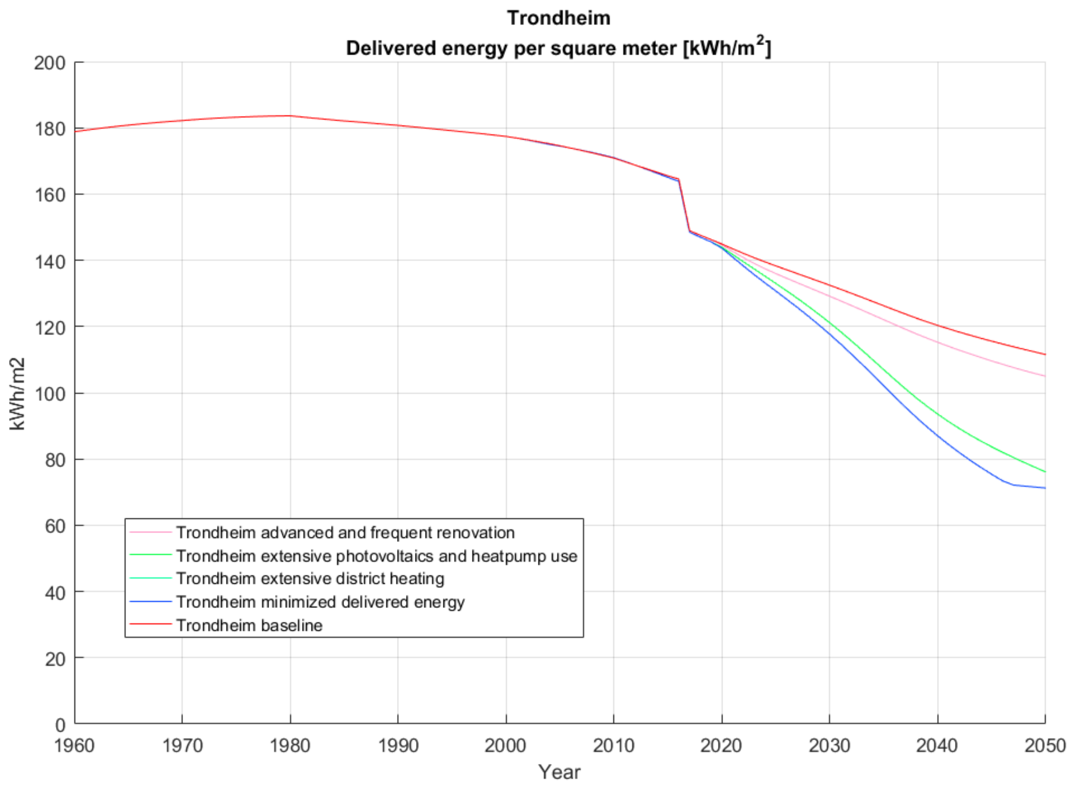


Figure 43: Estimated "real" delivered energy per m^2 to dwellings for different Trondheim scenarios. All purposes and uses.

Historically the estimated delivered energy intensity increased slightly from about 180 kWh/m^2 in 1960 and peaked at about 182 kWh/m^2 in 1980. Since 1980 it is estimated to have been decreasing to about 165 kWh/m^2 in 2016. In the future, the delivered energy intensity is expected to decrease further for all scenarios. The baseline 2050 result expects an energy intensity for the system to about 110 kWh/m^2. The other scenarios are expected to result in a higher energy efficiency and lower energy intensities with the estimated minimized delivered energy scenario energy intensity being the lowest at about 70 kWh/m^2 in 2050. The Trondheim minimized delivered energy curve is flattening in 2047 which is the same year that the amount of PV energy being generated is higher than electricity demand to heating and hot water. Modelled surplus PV contribution is then estimated as a contribution to electrical energy to appliances after 2047. This is somewhat unexpected and would either imply that it is converging to a point of the lowest estimated stock efficiency possible with the given estimations or an uncertainty in the methodology for those last few modelled years. The same flattening of the curve between 2047-2050 can also be seen in the other energy intensity estimations for this scenario presented later.

4.6 Comparison of Trondheim results and national results

The energy efficiency of the Trondheim dwelling stock and the Norwegian dwelling stock has been compared by plotting energy intensities for delivered energy to heating and hot water with and without AF correction in Figure 44. Both baseline scenarios and minimized energy scenarios has been compared. The historical estimated results show that the heating and hot water energy intensity for in the Norwegian average dwelling stock has been higher than Trondheim's dwelling stock for the period 1960-2016 both with and without AF correction. Future estimations done with and without AF correction also both points towards an expected future energy intensity that is lower for the Trondheim stock than the national stock. For all cases the future energy intensity is expected to decrease towards 2050.

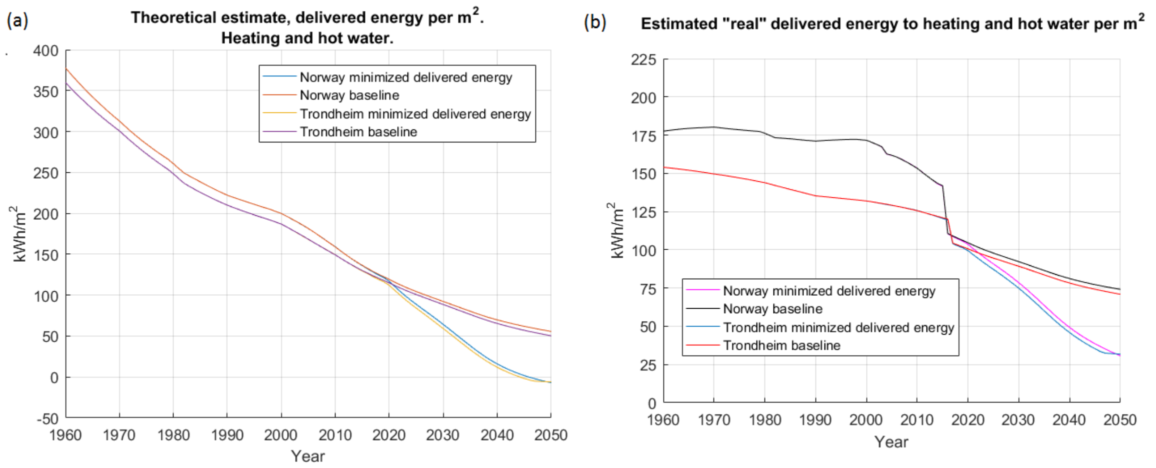


Figure 44: Delivered energy to heating and hot water per m² for Norway and Trondheim baselines and minimized delivered energy scenarios. Technical estimation (a) and estimated "real" delivered energy (b).

Now the energy delivered for electrical appliances is added to the total energy delivered and results are presented in Figure 45. As in the case for only delivered energy to heating and hot water the historical model results estimates a lower energy intensity for Trondheim's dwelling stock than the national average. In the future estimation, the total delivered energy per floor area is slightly higher for Trondheim than for Norway. The difference is very small and the likely explanation is the fact that the energy need to electrical appliances is modelled per dwelling and not per square meter. As Trondheim has a larger share of compact dwellings with an average floor size smaller than detached dwellings this results in a larger delivered energy to electrical appliances contribution per m^2 which compensates the lower energy need to heating and hot water.

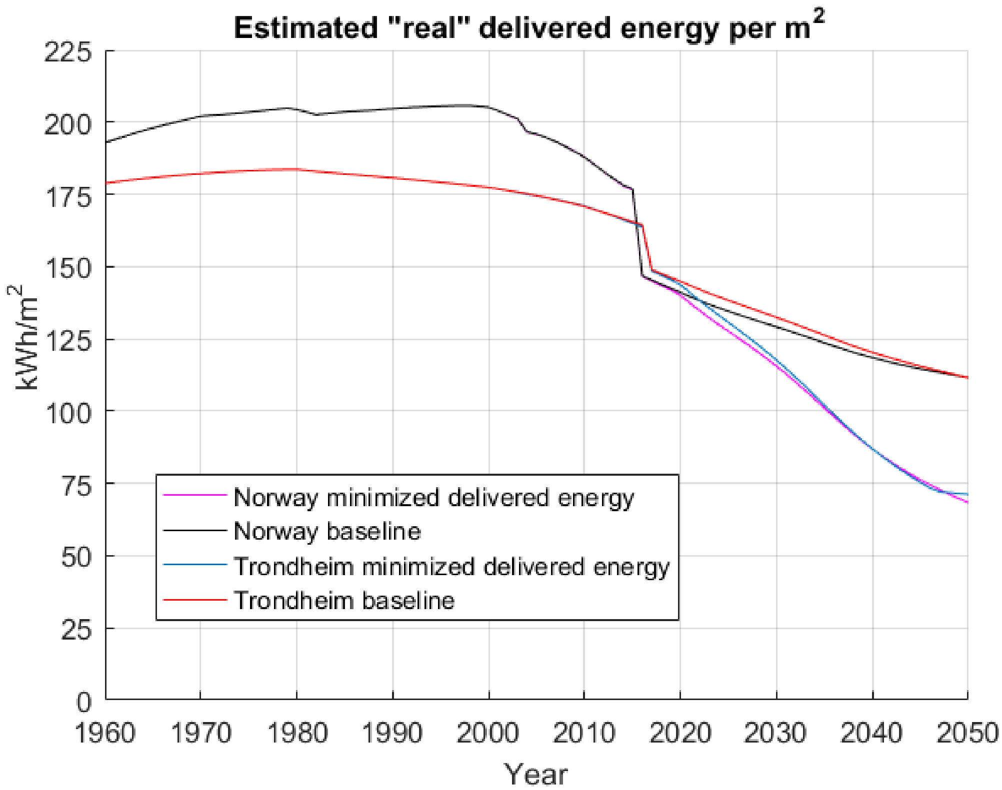


Figure 45: Estimated "real" yearly delivered energy to all appliances per m^2 for Norway and Trondheim baselines and minimized delivered energy scenarios.

A further comparison was then done on a per person level by dividing the estimated total delivered energy to heating and hot water by the population. The estimated historical delivered energy per capita is higher on the national level than on Trondheim level. On the national level above 5 MWh per person is estimated in 1960 with an estimated increase to about 8 MWh per person in 2000 before a decrease to less than 7 MWh per person in 2016. These numbers are estimated as historically lower for Trondheim. In 1960 the yearly delivered energy to heating and hot water is estimated to about 4 MWh per person with a steady increase to a peak above 5 MWh per person in 2000 before declining slightly to 2016.

In the future for the baseline Norway scenario a further decrease to almost 3 MWh per person is expected. The minimized delivered energy scenario is expected to result in a decrease to about 1 MWh per person in 2050 for the national case. The baseline Trondheim yearly delivered energy to heating and hot water per person is expected to converge towards about the same numbers as for the national case in 2050. For Trondheim's minimized delivered energy scenario the 2050 expectation is in line with the national case with about 1 MWh per person. Note that PV contribution is modelled directly as a decrease in delivered electricity to heating and hot water until all the electricity demand to heating and hot water is covered by PV. Estimated real yearly delivered energy to heating and hot water is presented in Figure 46.

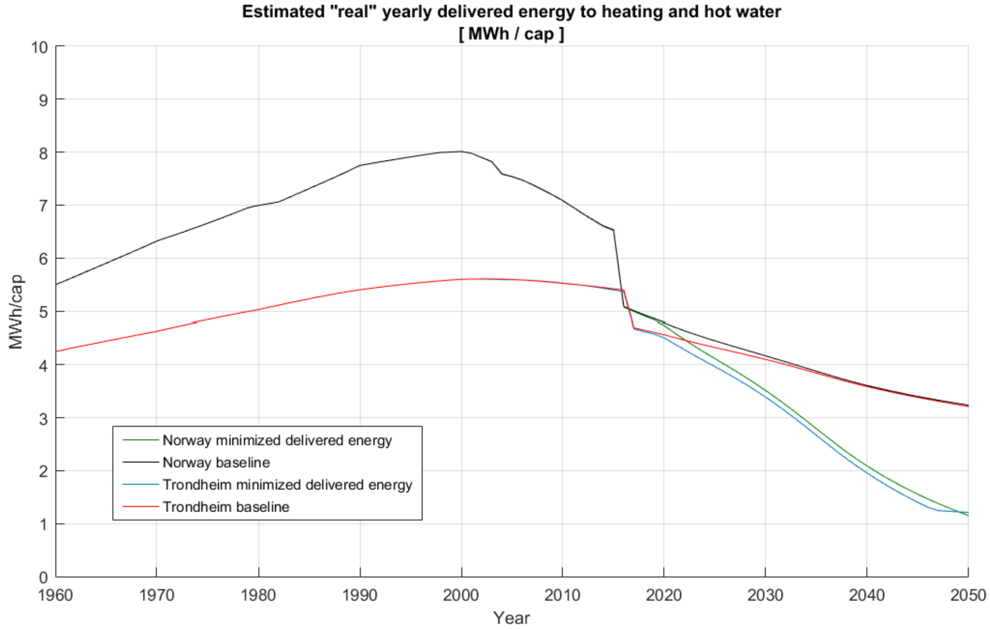


Figure 46: Estimated "real" yearly delivered energy to heating and hot water [MWh/cap] to dwellings in Trondheim and Norway for baseline and minimized delivered energy scenarios.

By adding delivered energy to electrical appliances to the total energy delivered the same trends can be observed as for heating and hot water. An increase in the delivered energy per person from 1960-2000 is also estimated here for both the Trondheim and Norway cases. The total delivered energy per person is expected to decrease towards 2050 from about 7 MWh per person in 2016 to less than 6 MWh per person in 2050 for baseline scenarios and about 3 MWh per person for minimized delivered energy scenarios. The estimated yearly delivered energy per person to heating, hot water and electrical appliances is presented in Figure 47.

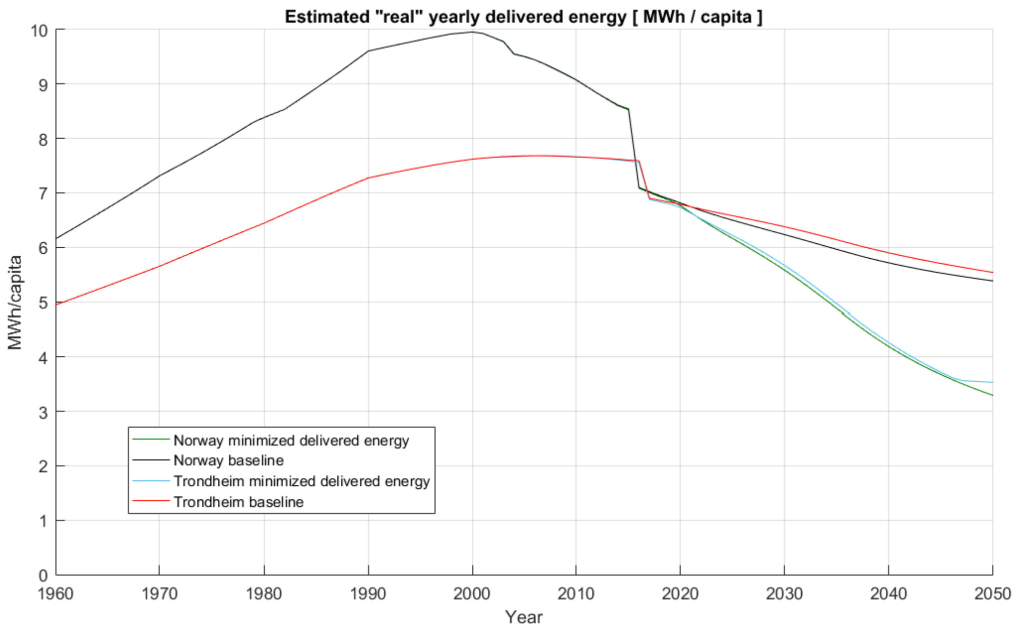


Figure 47: Estimated "real" yearly delivered energy [MWh/cap] to dwellings in Trondheim and Norway for baseline and minimized delivered energy scenarios.

4.7 Comparison of modelled delivered energy with statistics

To assess the uncertainty in the historical delivered energy model the estimated delivered energy to Trondheim's dwelling stock is compared with statistical gathered data. Total estimated delivered energy to the stock is compared with statistics in Figure 48. Data for all energy carriers has only been obtained for 5 years and this lack of data represents an uncertainty. Still the model results seem to match well with the 5 data points gathered.

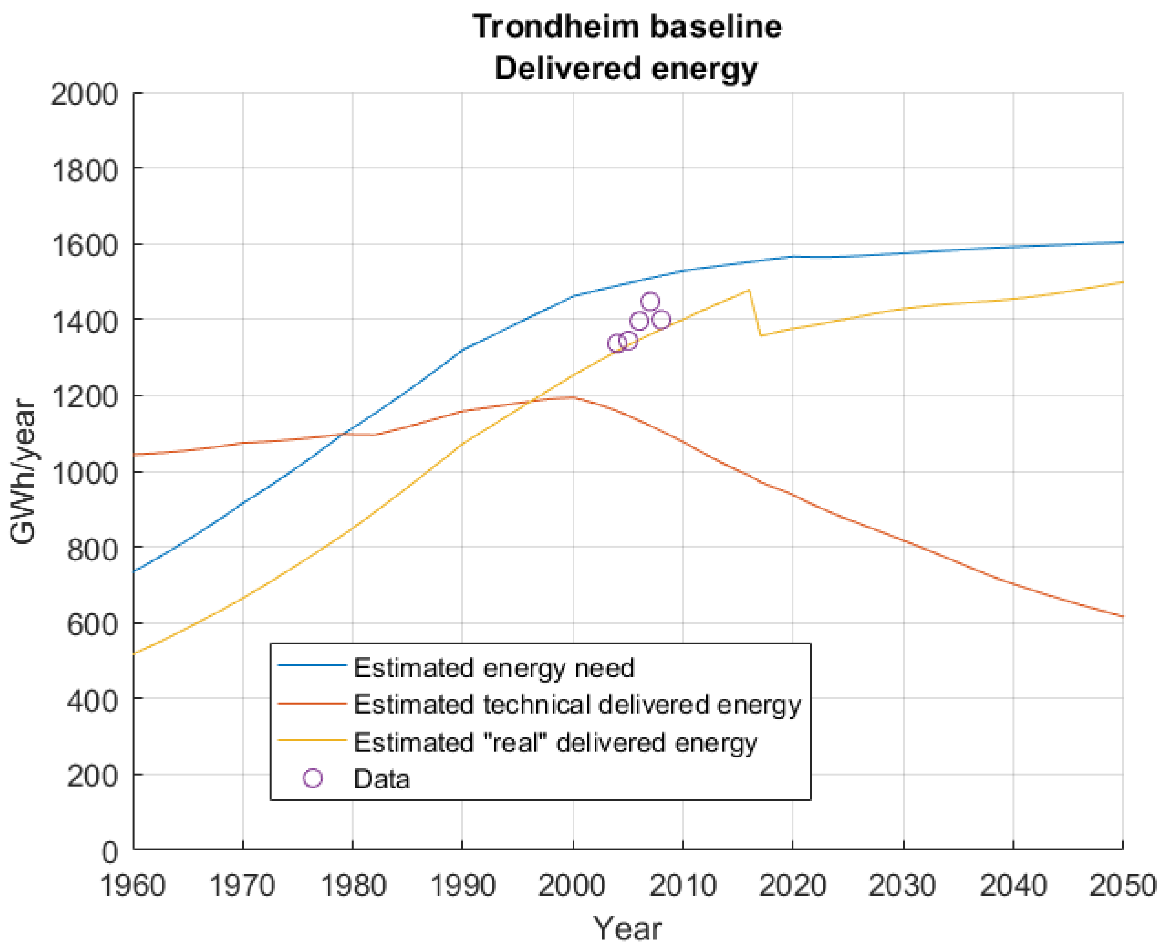


Figure 48: Comparison of estimated energy need, technical and "real" total delivered energy to Trondheim's dwelling stock together with statistical data.

A broader set of statistical data has been obtained for delivered energy from specific energy carriers. Model results giving delivered energy per year per carrier is plotted with statistical data for delivered energy from each carrier in Figure 49. Model results seems to match well with gathered data for all carriers. For electricity, data has only been found for years between 2004-2016. Figure 49a show that the technical estimated delivered energy from electricity has historically been larger than the "real" estimated delivered energy adjusted for user behavior due to the prebound effect. In the future, the technical estimate is predicted as lower than the "real" estimate. This is due to the rebound effect. The same trend can also be seen in Figure 49 b-d for biofuels, district heating and oil. Looking only at the data for biofuels it seems at a glance like the delivered energy from biofuels has been increasing rapidly from 1990. This is not the case as there is reason to believe that the 1990-2000 data are incorrect. According to Finstad et al. (2004) there is a high uncertainty related to biofuels data on the municipal level. Biofuels is known as a source of energy that has represented a large share of the total delivered energy over time. District heating started in 1986 and the estimated real delivered energy from biofuels seems to correlate well with data. The same can be seen for the estimated real delivered energy from oil when comparing it to gathered data in Figure 49d.

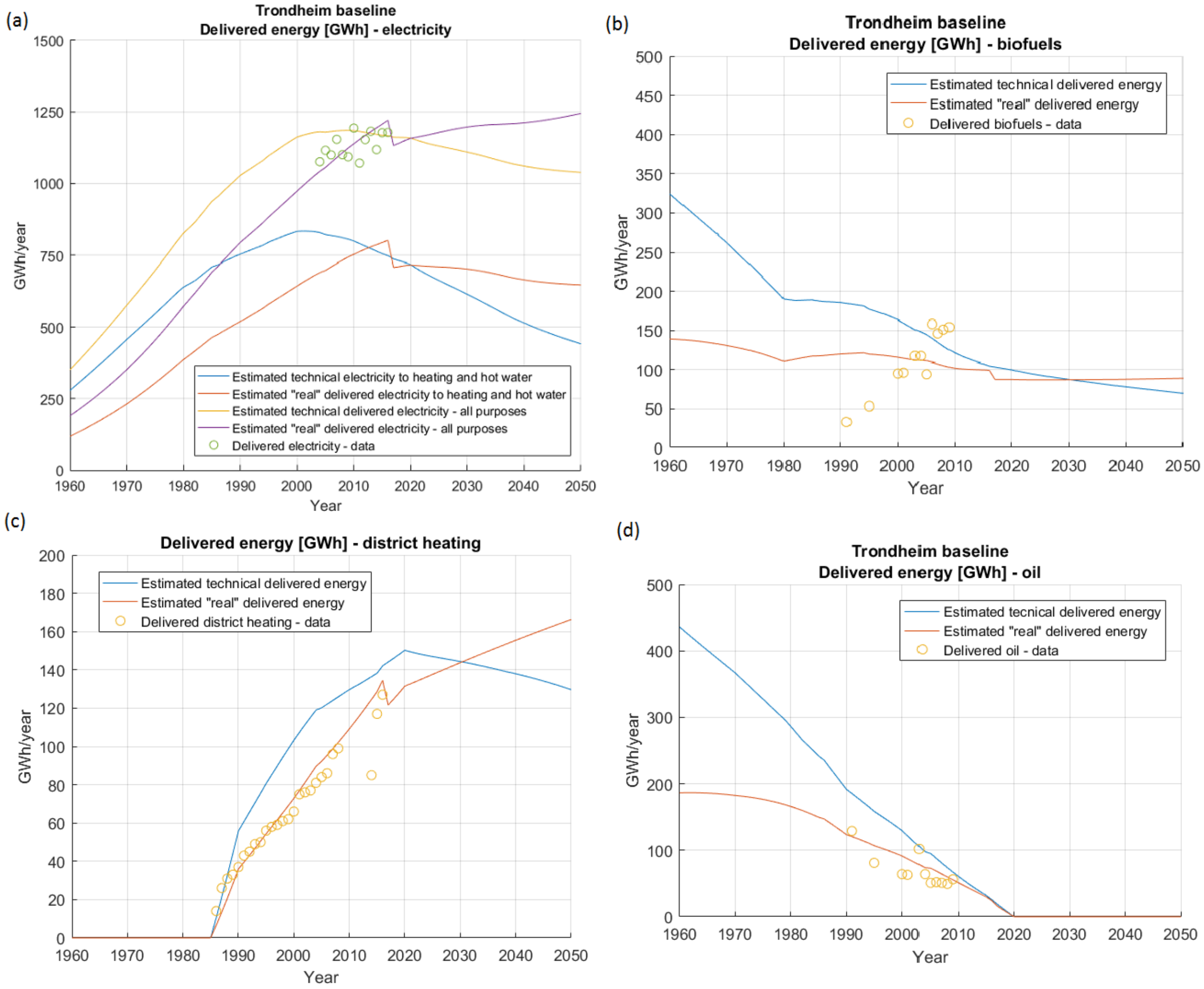


Figure 49: Comparison of estimated technical and "real" delivered energy per year for different energy carriers with statistical data. Plotted for electricity (a), biofuels (b), district heating (c), oil (d). Note different y-axis!

4.8 Sensitivity analysis

A sensitivity analysis on the different assumptions and inputs has been performed. Estimated delivered energy per year for many scenarios and different variants is given in Figure 50. The baseline 2050 result is estimated to about 1500 GWh. A change to an assumption using the high population growth estimation will result in a 2050 result of about 1700 GWh per year and an increase of about 13%. The minimized delivered energy scenario produce a 2050 result of about 950 GWh per year which is a decrease of about 37%. Additionally, the model was run without AF correction resulting in a 2050 decrease for the most optimistic scenario of 62%, which is a much larger decrease than with AF correction. This also points towards that the user behavior is an important parameter to the model results.

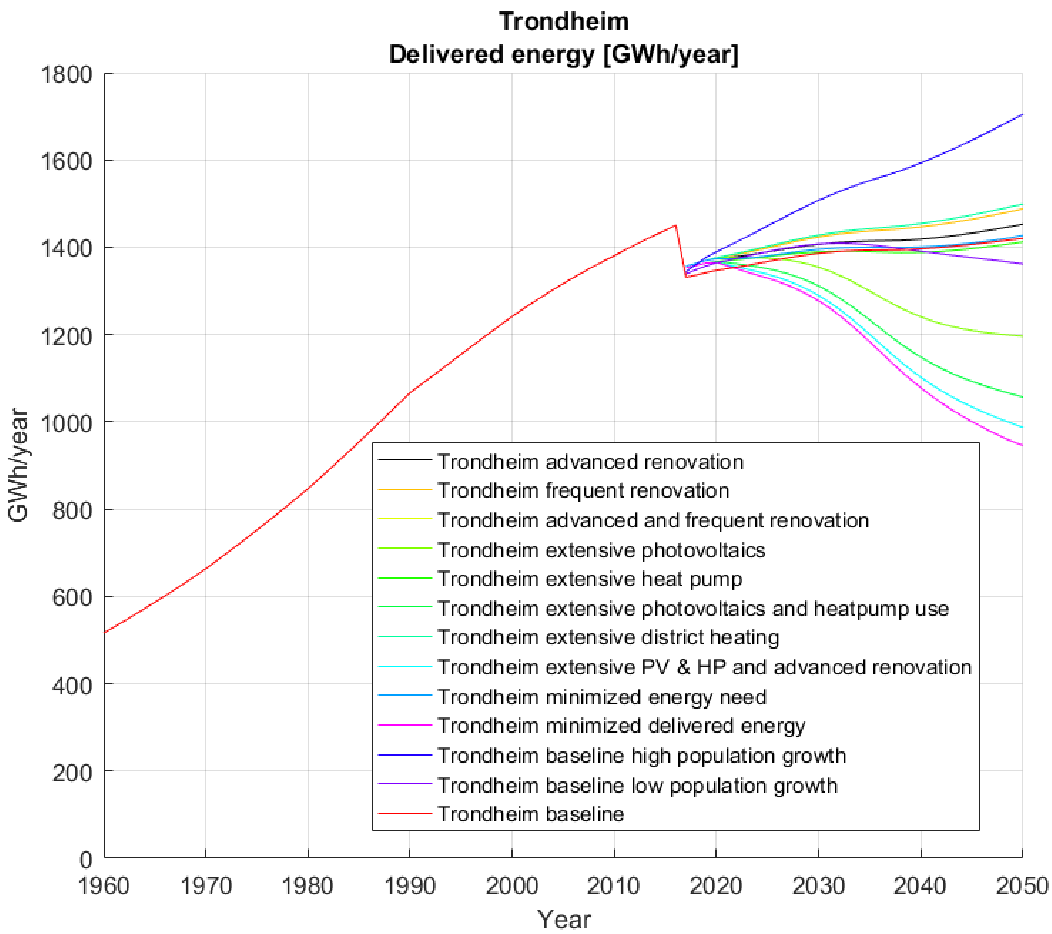


Figure 50: Estimated "real" delivered energy [GWh] to Trondheim Municipality for different future variants and assumptions.

Further population sensitivity analysis is performed by including the student correction together with the different future population high and low variants. Results are presented in Figure 51. A combination of a high future population growth and student correction gives an estimated result of about 1800 GWh per year in 2050 which is an increase of 20% from the baseline scenario. A baseline variant with low population growth will result in an estimated 1350 GWh in 2050 which is a decrease of 9%.

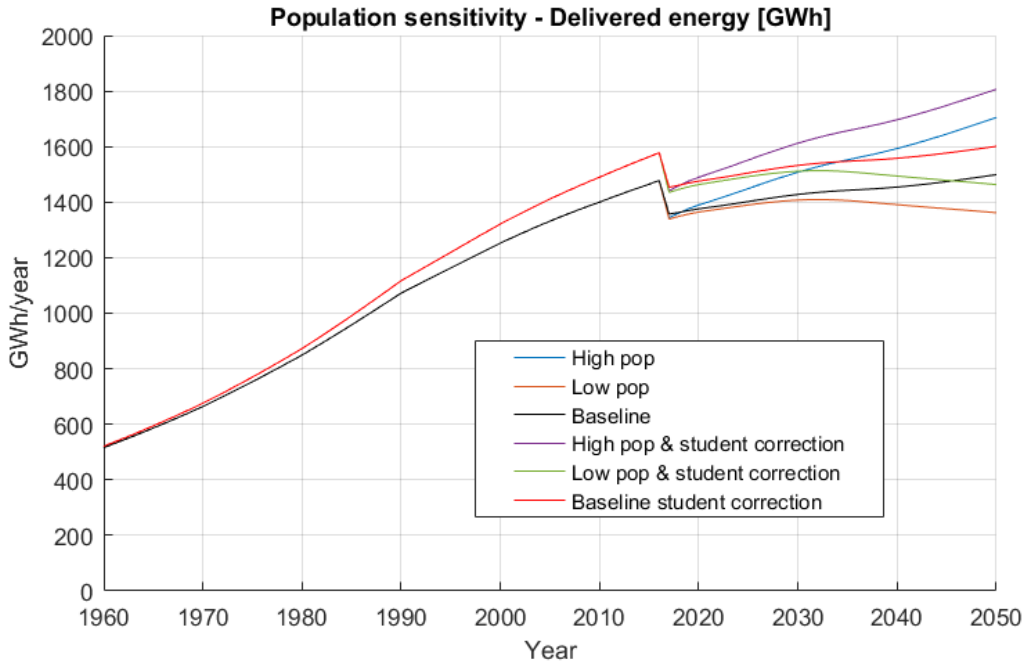


Figure 51: Calculated "real" delivered energy for six different future population estimations.

Sensitivity is then carried out on a delivered energy to the dwelling stock per square meter basis for many variants and presented in Figure 52. The baseline 2050 result is estimated to about 110kWh/m^2 with the other scenarios ranging from 115kWh/m^2 for the high population variant to 75 kWh/m^2 for the minimized delivered energy scenario which represents a decrease of 32%.

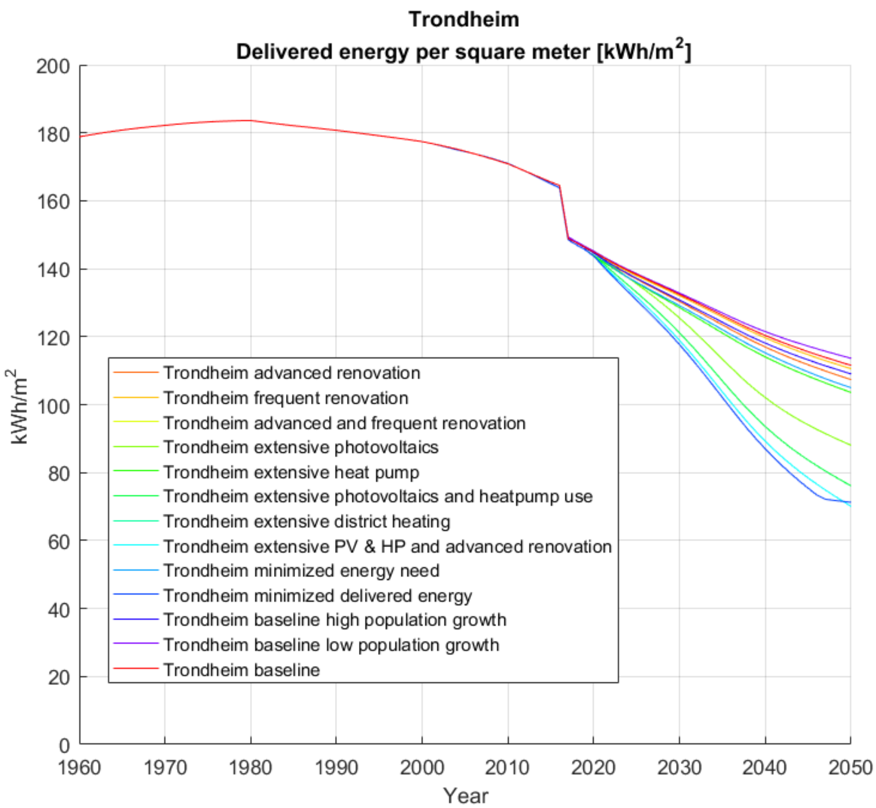


Figure 52: Sensitivity estimation for delivered energy per square meter for different scenarios and input variants.

5 Discussion

5.1 Main findings in relation to research questions

Previous work on delivered energy to the dwelling stock on the national Norwegian level has led to the need of a more regionalized analysis on the topic. A case study on the city of Trondheim was therefore performed to investigate possible differences between the national level and a regional level. The objective of this work has been to investigate the following research questions:

- *What will be the energy characteristics of the dwelling stock in Trondheim in 2050 compared to today and previous years?*
- *How does the energy use from the Trondheim dwelling stock differ from the national one?*
- *How could the Trondheim dwelling stock contribute to reaching national emission and energy efficiency targets?*

5.1.1 Historical and future Trondheim dwelling stock and energy characteristics

The first research question to be discussed is the following:

What will be the energy characteristics of the dwelling stock in Trondheim in 2050 compared to today and previous years?

To understand the energy characteristics of the dwelling stock it is first needed to create an understanding of the composition of the dwelling stock itself. The energy characteristics of the stock were then developed from this knowledge.

Dwelling stock evolution and activities

The building stock part of the model use population and person per dwelling P_D over time as input. Historically much statistical data is available and the parameters and corresponding dwelling stock estimations can be considered as quite accurate. However, the future estimation of these parameters represents a challenge as different assumptions and estimations for population growth leads to a wide range of results. These parameters are influenced by underlying drivers like demographics and socio-economic conditions and urbanization. Sensitivity analysis performed on the dwelling stock model presented in Appendix B and Figure B.1 shows that population is the parameter that affects the result the most.

In 2016 detached dwellings represented 61% of the stock which can be further split into 28% SFH and 33% TH together with 39% MFH dwellings. The model seems to estimate the cohort dwelling stock distribution well. The dwelling stock in Trondheim has historically been increasing and is expected to keep increasing in the future for both compact and detached dwellings. A growth of about 35% towards 2050 from present day is expected for the total stock out of which most the growth is expected to come in the MFH segment. Historically, modelled construction rates of dwellings per year has been increasing steadily since 1800 to present day. Accordingly, modelled renovation and demolition rates has also been increasing with the growing dwelling stock. Towards 2050 a further increase in the growth rates of dwellings per year for construction, renovation and demolition activity.

Comparison with statistical data for the period 2008-2016 shows a modelled overestimation of new constructed dwellings for the period. This represents an uncertainty, but the years compared are also the period after the financial crisis happened and this could be a reason for the error. This seems to point towards that the model has trouble capturing short term high or low conjunctures. However, the model seems to be doing very well in capturing the long-term development of the stock due to the population's need for housing. The number of modelled dwellings per year in stock seems to correlate well with available statistical data.

Historical energy characteristics

Historically the energy need in Trondheim's dwelling stock has been increasing from a technical estimated 750 GWh per year in 1960 out of which about 650 GWh of the energy need was to heating and hot water and the rest to electrical appliances to about 1550 GWh per year today. Out of the 2016 technical estimated energy need 1100 GWh per year is to heating and hot water and the rest to electrical appliances.

The estimated baseline "real" delivered energy results is historically estimated as lower than the technical estimated energy need. This is due to applying the climate HDD and user behavior AF corrections. The average yearly temperatures in Trondheim has changed over time changing the need for heating in the system. User behavior has also been showed to change over time by Sandberg et al. (2017) and the AF factor is applied to correct for the prebound and rebound effect in real energy use and the theoretical estimate.

The historical modelled baseline delivered energy to the system shows an increase from about 500GWh in 1960 to about 1500GWh today. Additionally, a HP contribution to heating and hot water of about 100 GWh is estimated today. Looking at the energy mix in the modelled results a large decrease in the use of oil as energy carriers has happened an estimated 190 GWh per year in 1960 to about 25GWh per year today. District heating started in 1986 and has grown rapidly. Today the delivered energy from district heating to dwellings in Trondheim is about 130 GWh per year which represents about 9% of the total. This share is somewhat larger than the district heating share seen in delivered energy to households in Oslo which according to Table 10577 at Statistics Norway (2017) was 4% in 2009 and 6.7% in 2012. It is much larger than the national average district heating share of 2% in 2016 found by Sandberg et al. (2016). This difference is likely because district heating is more economically attractive and sustainable in areas with high population density. It is more difficult for a company to make a profit on district heating in the countryside where long distances and low population density leads to the need for a larger infrastructure and higher cost per customer. Therefore, it is as expected that the district heating share of the energy mix is larger for cities than the national average. Biofuels is estimated to have stayed between 150 and 100 GWh for the whole period with the trend being a total decrease from 1960-2016. It is important to remember that the historical modelled delivered energy mix is based on the national average from 1960-1980 and the energy mix uncertainty in this period is especially high. From 1986 towards present day various data has been gathered and the model has been calibrated towards these.

Looking at cohort specific energy use in Figure 42 it is estimated that energy delivered to older cohorts has been going down over time. Comparing 1970 values with 2016 values for cohort 1 shows a 29% reduction in delivered energy to the cohort. This points towards that an improved energy efficiency has already been achieved through standard renovation of older dwellings.

Future energy characteristics

To estimate the future development of Trondheim's dwelling stock's future energy characteristics a scenario analysis has been done. A business as usual baseline scenario has been used as the basis for the calculations. The findings suggest that a business as usual renovation, system efficiency and PV and HP share development towards 2050 will result in a small growth in delivered energy to the system of about 1%. An out phasing of oil as energy carrier to the dwelling stock is expected in line with energy policies in 2020 (Miljødirektoratet, 2017; Ministry of The Environment, 2012). Delivered energy from district heating is expected to grow with about 25% from present to 2050 while delivered energy from biofuels is expected to stay about constant. The HP contribution of delivered energy to the stock is expected to grow with about 250% from the present contribution over the period. PVs are expected to be implemented gradually from 2020 and reach about 60 GWh in 2050 for the baseline scenario.

As the dwelling stock in Trondheim is expected to grow in the future while the baseline results suggest a constant trend in delivered energy this implies a more aggressive use of local energy sources as already mentioned and higher energy efficiency in the dwelling stock. The increased energy efficiency is seen in the calculated "real" energy intensity [kWh/m^2] results from Figure 43 with a baseline reduction of about 35% from present day to 2050. It is also interesting to investigate how future renovation will affect delivered energy to different cohorts. Taking another look at cohort 1 in Figure 42 shows a 69% reduction in delivered energy in 2050 compared to 1960. This represents a 42% reduction compared with present day delivered energy to the cohort and implies that the building stock will become more energy efficient.

Scenario discussion

Four additional scenarios have been developed and results were shown in Figure 39 for all four scenarios. Scenario 1 is the extensive PV and HP scenario and aims to mimic a potential future where policies and measures are taken to create broad implementations of photovoltaics and heat pumps in the dwelling stock. In this scenario, a large increase of PV and HP contributions is shown to lead to a corresponding decrease in delivered energy to heating and hot water. A total reduction of delivered energy of 30% is expected from present day towards 2050. In comparison scenario 2 advanced and frequent renovation is expected only to lead to a 5 % reduction in total delivered energy for the same period compared to baseline. This points towards that a lot of the potential energy efficiency gains from renovation will also be reached through natural standard renovation over the period. The extensive district heating scenario does not aim at reducing delivered energy to the system, but rather making it possible to shift the energy mix towards a higher district heating share. This can then make it possible to free surplus electricity that can be used to replace dirtier energy carriers like gasoline in other sectors. A 250% increase in total delivered energy from district heating in 2050 compared to 2016 has been shown to be possible with the scenario assumptions. This represents about two third of the delivered energy to heating and dhw in 2050 for the given scenario. The minimized delivered energy scenario combines all the three others and is the most ambitious scenario considered. An expected total delivered energy reduction of 37% is expected in this scenario with an 81% district heating share of delivered energy to heating and hot water. It has been shown in this work that extensive use of local energy is expected to have the largest potential for energy savings in Trondheim's dwelling stock. The possibilities for shifting delivered energy to district heating is also large.

Sensitivity analysis

A sensitivity analysis was run for different future variants and assumptions in Figure 50. Compared to baseline the largest increase in expected delivered energy was shown by combining high expected population growth variant with the student correction. This gave a result 20% higher than the baseline result. A low population growth variant provided a 2050 result that was 9 % lower than baseline result. This points towards that population is an important parameter. The lowest result was seen for the minimized delivered energy variant with a total reduction of 37%. Looking at the sensitivity estimation of energy intensities in Figure 52 a resulting range of 75-117 kWh/m^2 is seen with a baseline result of about 115 kWh/m^2 which implies a percentage result range of +1% to -35% compared to baseline.

Additionally, it was seen that the thermal adaption factor has a large impact on the result. The technical estimated decrease of 62% of delivered energy in 2050 to Trondheim's dwelling stock compared with 2016 was recalculated to a 37% decrease after the user behavior correction. This predicted rebound effect has a very large impact on results and it is important to make sure this parameter is estimated as good as possible.

5.1.2 Comparison with the national level

The second research question explored is the following:

How does the energy use from the Trondheim dwelling stock differ from the national one?

First the dwelling stock compositions of Trondheim and Norway is compared. This then gives a base to discuss the energy characteristics of the stocks.

Stock composition

The composition of the national dwelling stock has been shown to vary in composition between European countries (Sandberg et al., 2016). It has been viewed as likely that stocks might also vary on a regional level within and between countries because of several factors such as climatic conditions, economic factors and historical population growth.

Comparison of results for Trondheim with results from the national level for selected countries obtained by Sandberg et al. (2016) was done in Figure 36. The 2050 growth in Trondheim compared to present day of about 35% corresponds well with the national expected stock growth. The share of the stock that belongs to both the given 1980-2020 and 2020-2050 cohort is modelled to become slightly larger in Trondheim than in the national Norwegian level's corresponding 1981-2015 and 2016-2050 cohorts. The share of older buildings constructed before 1980 is expected to be smaller in Trondheim than the national level. This can be seen in Figure 36. As the energy consumption of the dwelling stock is to a large degree decided by the stock composition it is likely that the energy characteristics in Trondheim differ from the national dwelling stock.

Energy characteristics

As expected the dwelling stock's energy characteristics has been shown to differ between the national average and Trondheim. Comparing total delivered energy carriers to the Norwegian dwelling stock from Sandberg et al. (2017) in Figure 8 and Trondheim's dwelling stock in Figure 40 it's clearly seen that the energy mix in Trondheim differs from the national energy mix at present. Trondheim has a larger share of district heating and a smaller share of biofuels in the mix. HP contribution is also estimated as relatively smaller in Trondheim with 7% compared with 12% nationally at present which is likely due to the stock composition differences with less SFH and TH dwellings in Trondheim. The estimated differences in energy intensity in 2050 are small between Norway and Trondheim. A larger difference was initially expected in energy intensities. The similar results might be a consequence of applying much of the same assumptions on similar scenarios.

In 2050 comparing baseline scenarios for Norway and Trondheim again from Figure 8 it is expected a slight decrease in total delivered energy in Norway, but for Trondheim it is expected a slight increase. This is somewhat surprising as the total dwelling stock growth is expected to be quite similar for both the national case and the regional Trondheim case. The relative difference does not seem to be very large however as the Trondheim expected baseline delivered energy growth is at about 1% while the Norway decrease is about -1%. This could be explained by a larger expected population growth in Trondheim than the national average. 38% of the delivered energy to Norway's dwelling stock and 40% to Trondheim's stock is expected to go to electrical appliances in 2050. This difference is probably seen due to the way that energy to electrical appliances is modelled as a yearly kWh per dwelling value considering that Trondheim has a lower P_D than the national average. Trondheim 2050 is also here expected to have a larger district heating share than national expectations and Norway is expected to have a higher biofuel share. While electricity is expected to cover 83% of the Trondheim delivered energy in 2050 it is expected to cover 85% nationally. Delivered energy to heating and hot water is expected to go down for both baseline cases between 2016 and 2050 and is expected to represent a share of 60% in Trondheim and 62% nationally of total delivered energy to the respective systems in 2050.

The scenario analysis has provided the same main findings for Trondheim's dwelling stock as the national stock. It has been shown for Trondheim that the measures that are expected to lead to the largest decrease in delivered energy in 2050 is an extensive implementation of local PV and HP energy contribution. An advanced and frequent renovation policy is also expected to lead to energy savings, but on a smaller scale. This has been shown to be because much of the older dwelling stock in Trondheim that has the largest potential for energy efficiency improvements will undergo renovation naturally by standard renovation. This is in line with the findings from Sandberg et al. (2017) that concluded that further ambitious and frequent renovation commonly mentioned as important ways to obtain energy savings were found to have only a limited effect on overall savings towards 2050. Sandberg et al. (2017) also found extensive use of local energy to be the measure with the largest potential for energy savings.

Comparing energy intensities to heating and hot water in the dwelling stocks from Figure 44 for Norway and Trondheim shows that Trondheim historically has had a lower estimated energy intensity than the national average. In 1960 the estimate for Trondheim was about 15% lower than the estimated national average. At present this is estimated to about 13%. This trend is expected to continue, but the gap is expected to tighten together with a solid energy intensity decrease both nationally and for Trondheim. The baseline expectation in 2050 is a 4% lower energy intensity of delivered energy to heating and hot water in Trondheim than the national average. The same trend can be seen for minimized energy scenarios where both the national average and the Trondheim intensity is converging towards each other towards a 2050 intensity around 35 kWh per m^2. By adding electricity to appliances to the delivered energy to get the total delivered energy for Norway and Trondheim as shown in Figure 45 the historical energy intensity has also here been estimated lower in Trondheim than the national average with a difference in both 1960 and 2016 of about 10%. Towards 2050 baseline energy intensities are expected to converge against each other at about 115 kWh/m^2 which is a reduction of almost 30% compared to 2016 levels. Minimized delivered energy scenarios is expected to lead to an energy intensity of about 70 kWh for both baseline cases.

On a yearly MWh per capita level the energy intensity trends follow much the same patterns as on a per floor area level. Historically the Trondheim delivered energy intensity per capita has been estimated as significantly lower than the national average in the range of 20-25%. Once again a decrease in energy intensity per capita is expected and the Norwegian average and Trondheim is expected to converge against the same 2050 result. This can be seen both for the baseline and for minimized delivered energy scenarios. For the baseline scenarios, a 2050 result of about 3.2 MWh per capita to heating and hot water is expected while the most optimistic scenario expects an energy intensity per capita of about 1.2 MWh per capita. The same historical trend can be seen for total delivered energy including electricity to appliances where Trondheim has a historical lower energy intensity than the national average. However, it is predicted that the Norwegian average will be slightly lower in 2050 by about 3%. This is a surprising result, but is probably due to the way that electricity to appliances is modelled where a constant yearly 4500 kWh per dwelling is assumed for all dwelling types, cohorts and archetypes. The lower P_D in Trondheim then leads to a higher delivered energy per person to electrical appliances than on the national average that has a slightly higher P_D.

Sandberg et al. (2017) gave great importance to the expected rebound effect that reflects changes in user behavior. This effect is expected to reduce the saving potential on a national level from 51% to 36% nationally for the most optimistic scenario. This effect is also spotted in Figure 48 for Trondheim's baseline that shows a technical estimated decrease of 40% turning to a 1% increase due to the adaption factor correction of expected user behavior. For the minimized delivered energy scenario that can be directly compared to the numbers presented by Sandberg et al. (2017) an expected technical delivered energy decrease of 62% is turned to an expected real decrease of 37%. Measures to prevent this expected change in user behavior will likely be important to reach ambitious environmental goals.

5.1.3 Regional contribution to emission and energy efficiency targets

The final research question to be addressed is the following:

How could the Trondheim dwelling stock contribute to reaching national emission and energy efficiency targets?

Through this work it has been shown that the dwelling stock in Trondheim has the potential to reduce its energy use towards 2050. The baseline scenario expects a constant future trend in delivered energy to the system and if no special measures are taken this is what is most likely to happen. However, this study has shown that by implementing policies that promotes advanced and more frequent renovation and an extensive implementation of PVs and HPs the need for delivered energy to the system will decrease. Additionally, the possibility of doing a broad implementation of district heating in Trondheim has been investigated showing that there is a large potential of moving delivered energy from electricity to district heating.

An extensive implementation of PVs and HPs has been shown to represent the largest potential for decreasing delivered energy to the system. Renovation policies as suggested in the advanced and frequent renovation scenario is also expected to lead to a reduction in delivered energy in 2050, but the reduction is smaller than in the extensive PV and HP scenario. The results points towards that it is more effective to promote local energy contribution than to force advanced methods of renovation as much of the possible increased energy efficiency will be reached anyway through standard renovation. An extensive implementation of district heating will shift the energy mix in delivered energy to heating and dhw and is expected to lead to about 66% district heating in this mix. The combination of all presented measures leads to an expected reduction of 37% of delivered energy in 2050 compared to baseline with a district heating share of 82% to heating and dhw not supplied locally by PVs or HPs.

If these measures are implemented the delivered energy to the system is expected to go down. Even though the Norwegian electricity mix is supplied by hydropower and has a low carbon intensity this decrease in energy demand from the dwelling stock can lead to the possibility of using the surplus electricity to replace more carbon heavy energy sources in other sectors. An extensive implementation of district heating in Trondheim can also help replace electricity use from the dwelling stock to other purposes. The global warming potentials presented in the literature study in chapter 2.1 show the GHG reduction potential of replacing fossil fuels with PV electricity or district heating. For instance, it is possible to expect a future where electrical vehicles have a much larger share than at present and surplus electricity can be used to power the car park and might further lead to a decrease of fossil fueled vehicles. Another possibility could be to use this surplus electricity in industry or to export electricity to Europe. Norway is connected to the Nordic electricity market and further to the European market. This could help reduce GHG emissions even on a European level by replacing dirty energy on the continent. If the electricity systems integrate further in the future, it is difficult to tell how the 2050 electricity mix in Norway will be. The European electricity mix is more carbon intensive than ours and if the energy trade booms this could lead to the Norwegian electricity mix becoming more carbon intensive. Given a scenario where the carbon intensity of the electricity mix increase above the carbon intensity of district heating it would be advantageous to replace electricity with district heating.

5.2 Strength and weaknesses

In this subchapter strength and weaknesses of the presented work is discussed in detail.

5.2.1 Strengths of the methods and models in this work

The methodology used in this model has provided detailed understanding of the city's dwelling stock composition and energy characteristics. It is the first time a dynamic segmented model has been used to study a regionalized dwelling stock and has proven to be a useful way to study potential consequences of future energy policies and measures. The findings of this work suggest that this methodology has the potential of becoming an important tool for policy making and testing of political targets both on a national level and a regional level.

The presented model has been shown to reproduce historical development of dwelling stock size, stock composition and energy characteristics to Trondheim's dwelling stock well. The segmentation of the model into types, cohorts and archetypes has proven to be useful in understanding how the stock has and can develop over time. The model is well suited to describe the long-term dynamics of Trondheim's dwelling stock. By applying energy analysis, the long-term dynamics of delivered energy to the stock can be analyzed. Different possible policy measures can be tested and compared with each other. The dynamic segmented Trondheim model also has the potential of being used for estimating material demand and waste flows, identifying energy efficiency potential and market opportunities in the city related to substitution of component or technical equipment in the stock.

Using the same methodology to analyze Trondheim as at the national Norwegian level done by Sandberg et al. (2017) allows for a complete comparison of results between the national and regional level. Differences in stock composition and energy characteristics are easily uncovered and can be used to improve the understanding of how regional policy making might be specialized towards local conditions to optimize policy results. It is not given that a national policy will have the same effect in a countryside region dominated by SFH dwellings with a low dwelling density as in a densified major city with a high share of MFH dwellings.

It has been a clear advantage to model the future energy mix of Trondheim by type, cohorts and archetypes. Especially when analyzing the potential of a future extensive district heating policy as it makes it possible to differentiate between dwelling types, include a change of heating system in renovation cycles and then through an analysis of energy use estimate when the change will happen. This allows for the possibility of a scenario comparison of dwelling stock's energy mix by comparing measures even within the stock composition itself.

5.2.2 Shortcomings and weaknesses

The model has been shown to be able to capture long term development of a regionalized dwelling stock, but it does not have the same ability to capture short term development such as a sudden drop in yearly construction rates in Trondheim as seen in Table 26. This was also seen at the national level in the work presented by Sandberg et al. (2014). Such a precision would require input parameters reflecting for instance socio-economic development.

As in any dwelling stock model the modelling of Trondheim has involved a great number of uncertainties affecting the results. In general, the uncertainty is larger the further back in time and the further into the future estimations are done. Historical population data provided by SSB (2016a) and SSB (2016b) in general represents a low uncertainty. However, the student population development is a factor of uncertainty as it has been shown that a large share of the students that lives in Trondheim is not registered as inhabitants in the municipality. Therefore, estimations have been performed to try to include this part of the population. The future demographic development in Trondheim is another source of uncertainty, and three scenarios for population forecasts provided by Trondheim Kommune (2016) has been used.

There is an uncertainty related to the fact that definitions have not been constant for the same terms. This is for instance described in the 1950 census by Statistics Norway (2016a) where the term "apartments" is discussed. According to this the lack of a definition has led to different use of the term at different census years. Another problem in the older censuses is the fact that Trondheim municipality historically has been split in several municipalities. This has led to a lack of found data for the whole present day Trondheim area in some years.

Statistics for delivered energy to Trondheim's dwelling stock was not found for earlier years than 1986. It was decided to assume national energy mix shares between 1960-1980 and then calibrate the model towards gathered regional data from 1980. This has led to a higher uncertainty in historical energy model results pre-1980 than post-1980. Historical statistics of energy mix within dwelling types and cohorts has been limited except for some years for district heating and it has therefore not been possible to estimate the energy mix within dwelling types with absolute certainty. According to Finstad et al. (2004) there is also a high uncertainty related to the gathered data of biofuels and oil use on a municipal level.

PV contribution has been modelled as a straight contribution to reducing the delivered electricity to heating and hot water. As seen in Figure 43 this results in a strong flattening of the curve for energy intensity for the minimized delivered energy scenario between 2047 and 2050 when the PV contribution becomes larger than the demand to heating and hot water. The surplus PV contribution are then modelled as a contribution to electricity to electrical appliances for 2047-2050. This flattening of the curve in Figure 43 is still unexpected and it could represent an uncertainty in the calculations. Another shortcoming with the modelled PV contribution is that it is only modelled on a yearly basis. PVs generate electricity when the sun is up and are most effective when there are no clouds. Most electricity will be generated during summer time when the demand to heating is at its lowest. This would likely involve electricity being fed to the grid. During winter time when the demand peaks and days are shorter less PV electricity is generated and dwellings will need more electricity delivered from grid to heating purposes.

5.3 Recommendations for future work

This work has dug into historical censuses, building data statistics, future population estimates, student estimations and other parameters to establish a model for the future Trondheim dwelling stock. An energy analysis has then been performed to estimate the historical energy use of the city and predict future energy characteristics of the city's dwelling stock. Based on the presented Trondheim model a range of further work could be of interest.

As seen in Table 4 the share of dwelling types within Trondheim varies after subareas of the city. It could therefore be useful to study and model an even smaller system like a city district or a neighborhood. In such a way potential energy policy making related to dwelling stocks might be analyzed on a city district level. This might lead the way to starting up low or zero emission neighborhood projects. A more bottom up analysis could even allow for individual buildings or dwellings to be modelled with individual characteristics as input.

The energy analysis that has been done in this work has laid the grounds for a future work on GHG emissions from Trondheim's dwelling stock. This would be a natural step as a follow up work. The potential for future GHG emission reductions can be identified through further scenario analysis. One idea could be to perform detailed research using LCA methodology analyzing the different specific energy carriers to the dwelling stock to calculate the global warming potentials for the specific carriers. Estimations can then be done to calculate total yearly carbon emissions from the dwelling stock. Furthermore, analysis can be done on how a change in carbon intensity for different carriers combined with a change in the energy characteristics of the stock will change the future carbon emissions for the stock.

Another interesting study would be a cost benefit analysis on the presented scenarios for Trondheim's dwelling stock. A life cycle cost analysis could be performed. In such a way, the economic feasibility for different measures could be predicted and the most socioeconomic profitable measures identified.

The energy analysis methodology should be improved to include potential methods for storage of energy or energy delivered to grid from PVs on a shorter time frame basis. Solar energy is a variable energy source. As it currently stands PV contribution is modelled on a yearly basis as a direct contribution to heating and dhw. This does not reflect the reality of seasonal weather changes and peak loads. The reality is probably that electricity will be fed to grid during summer and a higher amount of electricity will be delivered to the dwellings during winter when demand is higher and generation is lower. An energy storage system for PV energy like future installation of batteries for dwellings could be considered. Another possibility is a pumped storage hydropower system where surplus PV can be modelled as import and export to and from grid.

A new way to model electricity to appliances should be considered as the current method models a constant yearly kWh per dwelling to all dwelling segments, cohorts and archetypes alike. It is unlikely that a small MFH dwelling with a lower person per dwelling P_D has the same electricity demand to appliances as a larger SFH dwelling with a higher P_D. By instead modelling electricity to appliances as a input per segment, cohort and archetype a better understanding of this can be accomplished. It is possible that due to the current methodology the electricity to appliances demand in Trondheim is slightly overestimated as it has a larger share of MFH dwellings than the national average that the 4500 kWh per dwelling for all dwellings input is estimated for.

5.4 Implications of study

It was expected before the work on implementing a dwelling stock model for Trondheim municipality that it would give results showing that dwelling stocks on the regional level differed from the national level. In the same way, the expectation has been that the energy characteristics of Trondheim's dwelling stock will differ from the national average.

Somewhat surprisingly the simulated normalized total stock growth in Trondheim has been shown to correspond very well with the national Norwegian results from Sandberg et al. (2016). One explanation could be that due to poor data availability several of the assumptions done at the national level has also been implemented in the study of Trondheim municipality. Still the stock composition itself differs and the Trondheim stock currently has a larger percentage of buildings built before 1980 than on the national level. Similarly, the share of compact dwellings in Trondheim seems to be higher than on the national level. As the stock composition differs this will influence the need for renovation, demolition and construction activities. Therefore, the potential for energy reduction and improved energy efficiency in the building sector differs regionally within a nation.

This is also confirmed in the energy analysis. By comparing the historical and expected future energy mix to heating and dhw in Trondheim with the national average it has clearly been shown that there is a larger share of district heating in the mix in Trondheim. This trend is expected to continue in the future. Historically the dwelling stock energy intensity has been lower in Trondheim than the national average and this is due to the different stock composition. A decrease is expected in energy intensity towards 2050 both on a per floor area and per capita level. However, it is expected that the national and Trondheim energy intensities will converge towards each other and become more and more equal.

The scenario analysis has provided insight into the different roads the energy characteristics of Trondheim's dwelling stock might take the next 30 years. Assuming a business as usual development a small growth in delivered energy is expected. It has been shown that by implementing a series of measures it is possible to reduce delivered energy to the system in

2050 compared with today by one third. Compared with the business as usual development this is a potential difference in 2050 of 37%.

At the same time an extensive district heating policy in Trondheim can help lower delivered electricity to the stock and create surplus electricity that might be used to replace more carbon heavy energy sources in other sectors. A district heating policy would make sense in a city like Trondheim, but might not make sense in a countryside region with a low dwelling density. This implies that regionalized policies on building stock development, renovation activity and building energy performances will be very important to implement. It has the possibility to make an important contribution in achieving international and national goals of energy savings, energy efficiency and GHG emissions reductions. Regionalized dwelling stock models should be of great interest to local policy makers and stakeholders that wants to be part of the race towards a sustainable and green future.

6 Conclusion

Trondheim's dwelling stock energy use has been modelled over time using various assumptions and underlying models. The composition of the dwelling stock has been modelled through a mass-balance consistent and stock-driven segmented dynamic dwelling stock model. The model has provided understanding of the dwelling stock's changing composition over time in terms of dwelling type, cohort and archetype. Energy analysis has then been run on the dwelling stock to provide valuable insight to the energy characteristics of the stock. The scenario analysis has revealed possible roads of future development of system efficiencies, energy mix and total delivered energy to the stock that can be of great use to policy makers.

Trondheim's dwelling stock composition has been shown to be different from the national stock with a larger share of MFH dwellings and older archetypes. The energy mix has also been shown to differ from the national average. The main findings suggest that if the goal is to reduce the delivered energy to the city the focus should be on implementing extensive use of local energy from PVs and HPs. This has been shown to be the most effective measures. Much focus is often given to renovation policies, but the findings suggests that much of the potential energy efficiency improvements will be reached through natural standard renovation before 2050 and that the potential of further effects are limited. Measures should also be taken to limit the expected rebound effect. These findings are in line with the findings by Sandberg et al. (2017).

Additionally, it has been shown that Trondheim's dwelling stock has a large potential of shifting its energy mix towards district heating. This can help free surplus electricity that can then be used to replace other more carbon intensive energy sources in other sectors for instance by powering an electrical car park. By decreasing the energy use and by shifting energy carriers from fossil fuels to carriers with lower carbon intensities the Trondheim dwelling stock has the potential of contributing to reaching national and regional energy and emission targets. The next natural step now would be to do a further analysis of the dwelling stock's potential for contributing to reduced GHG emissions.

A regionalized segmented dynamic dwelling stock model is likely to become a powerful tool for local policy makers. It has been proven to provide valuable insight into dwelling stock composition and characteristics and provides the ability to run energy analysis on the long-term development of the dwelling stock. The ability to model the energy mix on a per dwelling type, cohort and archetype level has proven to be valuable. Future energy roadmaps can be created through scenario analysis and it allows for a comparison to be made between different considered policies on a long-term scale.

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Appendix

Appendix A: Energy delivered

Electricity

Data on delivered energy from electricity to dwellings in Trondheim Municipality has been provided by Statistics Norway (2017) and Trønder Energi (2017) for the period 2004-2016. Data on a municipal level for years pre-2004 has only been found on a regional level for Sør Trøndelag. A summary of gathered data is given in Table A.1. Statistics showing one year supply of electricity to dwellings in Trondheim for 2016 has been provided by Trønder Energi (2017) and is given in Table A.2.

Table A.1: Gathered data of histroical delivered electricity [GWh] to dwellings in Trondheim Kommune from various sources

Year	Electricty [GWh]	Source
2016	1178	Trønder Energi (2017)
2015	1177	Statistics Norway (2017)
2014	1118	Statistics Norway (2017)
2013	1182	Statistics Norway (2017)
2012	1153	Statistics Norway (2017)
2011	1071	Statistics Norway (2017)
2010	1193	Statistics Norway (2017)
2009	1092,9	Statistics Norway (2017)
2008	1100,3	Statistics Norway (2017)
2007	1153,9	Statistics Norway (2017)
2006	1099,7	Statistics Norway (2017)
2005	1115,3	Statistics Norway (2017)
2004	1075,7	http://www.ssb.no/a/magasinet/miljo/tab-2006-11-16-01.html

Table A.2: 2016 consumption of electrical power in Trondheim households.

Category	Estimated yearly consumption [kWh]
NEH-L: Nettleie for husholdningsformål	886731630
NEH-LV Nettleie for husholdning, sesongpris	1252011
NEH-S Nettleie for husholdningsformål	621025
NEH-LF Nettleie husholdning blokk	288684951

The net yearly consumption of electrical power by households in the Trondheim Municipality is given in Table A.3. Additionally, data for 2016 was provided by Trønder Energi (2017) and is given in Table A.4. The net yearly consumption of electrical power by households in the Trondheim Municipality is given in Table A.5.

Table A.3: Yearly net consumption of electrical power by Trondheim households during the period from 2010 to 2015 (SSB, 2016).

Year	Net delivered electrical power [GWh]
2010	1192,5
2011	1071,2
2012	1152,8
2013	1181,6
2014	1118,4
2015	1176,6

Table A.4: Data for delivered electricity [kWh] in 2016 to various consumer categories in Trondheim Municipality and description of the categories in Norwegian.

KOMMUNENAVN	Trondheim	
Radetiketter	**Antall av MÅLEPUNKT**	**Summer av EST_AARSFORBR**
NE3	1	1433112
NEG	481	13455539,9
NEH-L	53530	886731630
NEH-LF	35201	288684951
NEH-LV	97	1252011
NEH-S	29	621025
NEH-SF	3	15269
NER-3	5	227216199
NET-L	7080	152565361
NET-LF	1252	10317097
NET-S	205	13946174
NET-SF	11	184639
NEU-L	1118	1804363
NM3-1	15	129182696
NMH	14	1115361
NMT	3013	843063210
NMT-R	14	31220738
NMT-RX34	2	13932064
NMT-X34	3	6216696
Totalsum	**102074**	**2622958136**

TARIFFID	BESKRIVELSE
NEH-L	Nettleie for husholdningsformål
NEH-LV	Nettleie for husholdning, sesongpris
NEH-S	Nettleie for husholdningsformål
NET-S	Nettleie for næringsvirksomhet
NMT	Nettleie med effekt- og energiledd
NEH-SV	Nettleie for husholdning, sesongpris.
NFT-F	Nettleie med kun fastbeløp
NEH-LXO	Nettleie husholdning over 18000 kWh
NEH-LXU	Nettleie husholdning 18000 kWh
NET-XST	Nettleie Salvesen & Thams, maks
NET-XUF	Nettleie næringsvirksomhet u/fastledd
NEU-L	Nettleie
NET-L	Nettleie for næringsvirksomhet
NLP1	Pliktlevering kraft
NLP2	Pliktlevering kraft
NM3-1	Nettleie næring m/effektledd, høyspent
NET-LF	Nettleie næringsvirksomhet Blokkprodukt
NET-SF	Nettleie næringsvirksomhet Blokkprodukt
NEH-LF	Nettleie husholdning blokk
NMT-R	Nettleie med effekt/R.Eff- og energiledd
NEH-LX	Nettleie husholdning over 26280 kWh
NEH-SF	Nettleie for husholdningsformål
NE3	Nettleietariff høyspent u/effektledd
NET-LAVC	Avregning Enova og Forbuksavgift næring
NMH	Nettleie hush. med effekt- og energiledd
NMT-X34	Nettleie med effekt, energi og fast 20'
NMT-RX34	Nettleie med effekt/R.Eff- og energiledd
NER-3	Nettleietariff Regionalnett
NEG	Nettleie Gatelys
NFT-T	Nettleie med kun fastbeløp

Tabell A.5: Yearly net consumption of electrical power by Trondheim households during the period from 2010 to 2015 (SSB, 2016).

Year	Net delivered electrical power [GWh]
2010	1192,5
2011	1071,2
2012	1152,8
2013	1181,6
2014	1118,4
2015	1176,6

District heating

Data on delivered energy was provided by Statkraft (2017) and Brattebø & Reenaas (2012) and is given in Table A.6 and Table A.7. The share of energy carriers in the district heating energy mix has been given by Statkraft (2017a) as shown in Figure A.1.

Table A.6: Gathered data of histroical delivered energy from district heating [GWh] to dwellings in Trondheim Kommune from various sources.

Year	District heating [GWh]	Source
2016	127	Statkraft (2017)
2015	117	Statkraft (2017)
2014	85	Statkraft (2017)
2008	99	Brattebø & Reenaas (2012)
2007	96	Brattebø & Reenaas (2012)
2006	86	Brattebø & Reenaas (2012)
2005	84	Brattebø & Reenaas (2012)
2004	81	Brattebø & Reenaas (2012)
2003	77	Brattebø & Reenaas (2012)
2002	76	Brattebø & Reenaas (2012)
2001	75	Brattebø & Reenaas (2012)
2000	66	Brattebø & Reenaas (2012)
1999	62	Brattebø & Reenaas (2012)
1998	61	Brattebø & Reenaas (2012)
1997	59	Brattebø & Reenaas (2012)
1996	58	Brattebø & Reenaas (2012)
1995	56	Brattebø & Reenaas (2012)
1994	50	Brattebø & Reenaas (2012)
1993	49	Brattebø & Reenaas (2012)
1992	45	Brattebø & Reenaas (2012)
1991	43	Brattebø & Reenaas (2012)
1990	37	Brattebø & Reenaas (2012)
1989	33	Brattebø & Reenaas (2012)
1988	31	Brattebø & Reenaas (2012)
1987	26	Brattebø & Reenaas (2012)
1986	14	Brattebø & Reenaas (2012)

Tabell A.7: Yearly growth in district heating in kWh for all uses in Trondheim Municipality (Statkraft, 2017).

År	kWh
2001	31 000
2002	340 000
2003	990 343
2004	891 944
2005	1 167 000
2006	2 184 000
2007	2 879 000
2008	1 577 000
2009	1 150 048
2010	1 528 000
2011	1 876 000
2012	3 406 225
2013	2 628 000
2014	13 912 000
2015	8 463 867
2016	12 996 064
2017	353 377

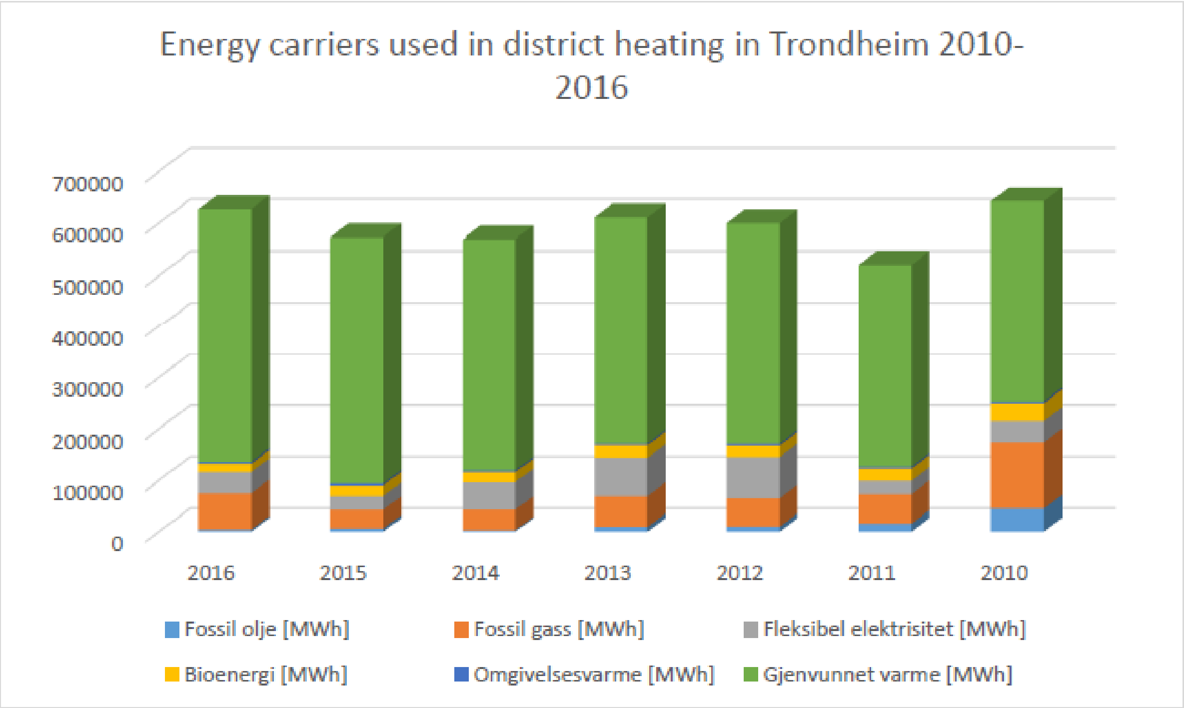

Figure A.1: Energy carriers share in district heating delivered energy to Trondheim Municipality for 2010-2016 (Statkraft, 2017a).

Appendix B. Dwelling stock composition

Data was found on the composition of the dwelling stock in Trondheim in 1980 and 2011 in Table 06266 at Statistics Norway (2016b). The data for 1980 is presented in Table B.1. 65% of the dwellings in Trondheim were detached and 35% compact in 1980. Data for 2011 is presented in Table B.2.

Tabell B.1: Dwelling stock composition of Trondheim in 1980 (Statistics Norway, 2016b).

Cohort	**Total**	**-1901**	**1901-1945**	**1946-1980**	**1981-2015**	**Unknown**
Total dwellings	53164	3226	9619	38044	-	2275
Detached dwellings	34327	2244	6611	23503	-	1969
Compact dwellings	18837	982	3008	14541	-	306

Tabell B.2: Dwelling stock composition of Trondheim in 2011 (Statistics Norway, 2016b).

Cohort	**Total**	**-1901**	**1901-1945**	**1946-1980**	**1981-2015**	**Unknown**
Total dwellings	92191	4297	10961	44458	30974	1546
Detached dwellings	56559	1635	6136	27151	20359	1278
Compact dwellings	35632	2662	4780	17307	10615	268

In 2011 the share of compacts has increased to 38 %. Strangely the number of total dwellings from before 1901 has increased and this could perhaps be partly explained due to the unknown category getting smaller. Another explanation could be that dwellings that were not in use in 1980 has now been occupied.

Dwelling stock sensitivity

Sensitivity on the dwelling stock modelling was run for population and P_D input and is given in Figure B.1. This show that population is the parameter that affects the result the most.

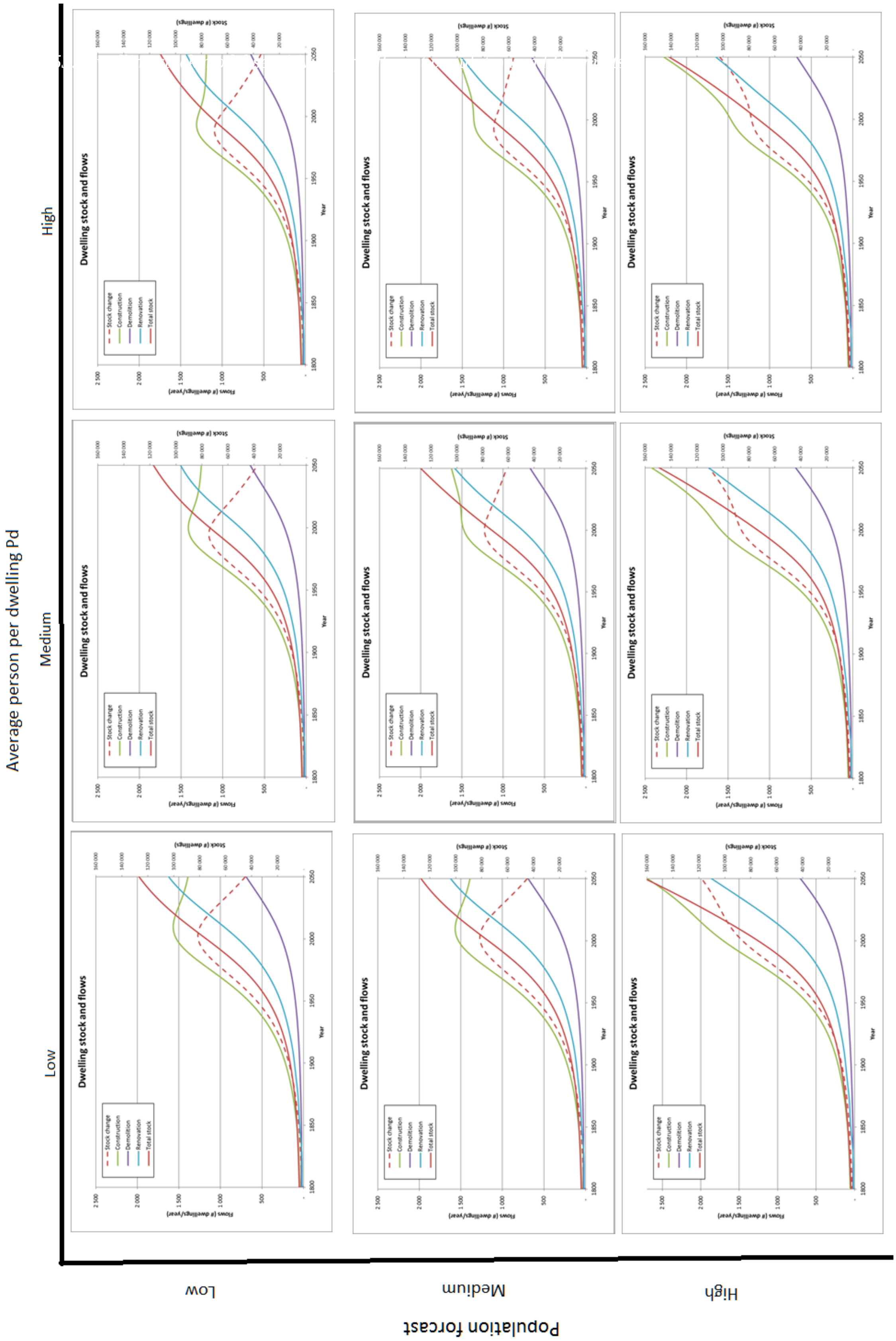

Figure 53: Dwelling stock model sensitivity for different population and PD inputs.