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Projection of electrical space heating potential as a demand response measure with use of thermal energy storage in the Norwegian residential building stock

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Renewable Energy

Preface

This concludes my time at the university of Ås. I want to thank Jon Gustav Kirkerud for excellent guidance throughout the work of my thesis and I also want to thank Nina Holck Sandberg which has been so collaborative under my time during the thesis and also for the use of her PhD results in this work. I want to thank Rasmus Elbæk Hedegaard, Steinar Grynning and Klodian Gradeci for answering questions and helping me during the work. At last I want to thank my mom and dad, Silje and to my friends Christian and Grunde.

Ås, 13th May 2019

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Abstract

The aim and goal of this thesis is to analyze and investigate the maximum potential of load shifting and delivered energy in the total Norwegian residential building stock quantified to different segments, building age classes and refurbishment states including usage of thermal energy storage in a demand response measure in the context of electrical space heating in Norwegian residential buildings quantified to the same segments in the stock in the period 1960-2100. The thesis will also analyze and investigate how and why a Norwegian wide-based demand response scheduling program may be integrated into the Norwegian power market in the future. Norway which is situated in a cold-temperate climate, use a significant share of electricity as the source for space heating. The thesis uses a building stock model developed by Nina Holck Sandberg at NTNU. Data gathered from a building stock energy model also developed by Sandberg is used to analyze and investigate the potential of electrical space heating and thermal mass. Segmentation of a building stock model into segments and cohorts gives detail insight into changing stock composition. The thesis uses a social science approach, therefore use of engineering modeling are excluded from the thesis. The estimated "real" delivered electricity as space heating in the total Norwegian residential building stock is found to be 17.9 TWh in 2019 and 11.4 TWh in 2050, while the maximum estimated load shifting potential is found to be 3.7 GW in 2019 and 2.3 GW in 2050. Effective thermal capacity is calculated in a bottom-up accounting model with a theoretical assumptive-intuitive rule-of-thumb approach quantifying interior partitions with a variation of different materials, which possess dissimilar thermal attributes including adjacent ratios of window to wall, internal wall and wall to floor. The total available effective heat capacity in the total Norwegian residential building stock is found be 11.9 GWh/K in 2020 and 16.1 GWh/K in 2050.

Keywords – Demand response; Load shifting; Residential; Building stock; Electrical heating; Variable renewable energy; Flexibility; Thermal energy storage; Thermal mass

Sammendrag

Formålet med denne studien er å analysere og undersøke maksimalt potensial av flytt av last i tid og levert energi i den totale norske bolig-bygningsmassen delt inn i ulike segmenter, konstruksjons-årsklasser og renoveringstilstander, inkludert bruk av termisk energilagring i et forbrukerfleksibilitetstiltak i konteksten av elektrisk romoppvarming i norske boliger delt inn i de samme segmentene i bygningsmassen i perioden 1960-2100. Avhandlingen vil også analysere og undersøke hvordan og hvorfor et storstilt norsk forbrukerfleksibilitetsprogram kan bli integrert i det norske kraftmarkedet i fremtiden. Norge som er lokalisert i et kaldt temperert klima, bruker en betydelig andel elektrisitet som kilde til romoppvarming. Avhandlingen bruker en bolig-bygningsmassemodell utviklet av Nina Holck Sandberg ved NTNU. Data som er samlet inn fra en bolig-bygningsmasse energimodell, også utviklet av Sandberg, brukes til å analysere og undersøke potensialet for elektrisk romoppvarming og termisk masse. Segmentering av en bygningsmassemodell i segmenter og kohorter gir detaljert innsikt i endring av bestandssammensetningen. Avhandlingen bruker en samfunnsvitenskapelig tilnærming, så bruk av ingeniørmodellering er utelukket fra avhandlingen. Den anslåtte «virkelige» leverte elektrisiteten som romoppvarming i den totale norske bolig-bygningsmassen er funnet å være 17,9 TWh i 2019 og 11,4 TWh i 2050, mens maksimal potensial av flytt av last i tid er funnet å være 3,7 GW i 2019 og 2,3 GW i 2050. Effektiv termisk kapasitet beregnes i en «bottom-up» modell med en teoretisk intuitiv «rule-of-thumb» metode som kvantifiserer innvendige bygningsdeler med en variasjon av forskjellige attributter, inkludert forhold mellom vindu og vegg, indre vegg og vegg til gulv lagt til grunn. Den totale tilgjengelige effektive varmekapasiteten i den totale norske bolig-bygningsmassen er funnet å være 11,9 GWh/K i 2020 og 16,1 GWh/K i 2050.

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List of abbreviations

DH	District Heating
DHW	Domestic Hot Water
DR	Demand Response
DSO	Distribution System Operator
HDD	Heating Degree Days
HP	Heat Pump
ICT	Information and Communications Technology
IEA	International Energy Agency
IEE	Intelligent Energy Europe
MFH	Multi Family Houses
nZEB	Nearly Zero Energy Building
PCM	Phase Change Materials
PV	Photovoltaic
RES	Renewable Energy Sources
SFH	Single Family Houses
TES	Thermal Energy Storage
TH	Terraced Houses
TSO	Transmission System Operator
VRE	Variable Renewable Energy

1 Introduction

Residential buildings have had a steady share of 20% of total final energy consumption in Norway in the period 2000-2015 (Lien & Spilde 2017), while considering only stationary energy use in mainland Norway, residential buildings stands for approximately two-thirds of total final energy use (Magnussen et al. 2012). Because of the cold-temperate climate Norway is situated in, space heating is by far the single-most important end-use demand in the Norwegian residential building sector (Magnussen et al. 2012; Sandberg 2017). Space heating in Norway is covered by different energy carriers. While biomass and district heating have some importance in some segments of the residential building sector, Bøeng et al. (2014) reported that based on heating equipment used in Norwegian dwellings, 96% of the dwellings used electric-based equipment. The importance of electrical heating has been of great importance in the country concerning end-use activity in the residential sector and are projected to continue further. With that in mind, the present power system in the Nordic region is experiencing a considerable structural change in terms of increased integration and transmission capacity and in terms of the composition of generation technologies (IEA 2016a; Kirkerud et al. 2014; Norden 2015; Söder et al. 2018; Tveten et al. 2016a; Tveten et al. 2016b). Subsidized and non-subsidized power production from renewable energy sources (RES) competes and partially replaces conventional thermal power production as Nordic climate policy agendas are among the most ambitious in the world (Bartelet et al. 2018a; Kipping & Trømborg 2017; Kirkerud et al. 2017; Lund et al. 2015; Tveten et al. 2016b). Because of increasing transmission capacity between Nordic countries and to continental Europe including increased market and regulatory efficiency, cross-border trading increases in the Nordic power market (Kirkerud et al. 2014; Statnett et al. 2016). Because of a present and predicted future complex power market in the Nordic region, the system will endure tests and challenges in the foreseeable future. The Nordic Transmission System Operators (TSO) have synchronously identified challenges and objectives in the Nordic region which will be a case of concern in the future going forward. Concerning the power market, they identify the need for flexibility in the system, to be able to deliver adequate transmission and sufficient generation capacity, including maintaining satisfying frequency quality and sufficient inertia (Statnett et al. 2016). Especially flexibility, which is a topic in this thesis, is of great importance going forward. Along with attempting to achieve these goals set in the future, demand in the system must be able to meet fluctuating production at each time point (Albadi & El-Saadany 2008; Grønborg 2016; IEA 2016b; Lund et al. 2015; Norden 2014; Norden 2015). As Lund et al. (2015) points out, in a traditional power system, the balancing operation is handled through a portfolio of different kind of power plants, which together are able to provide capacity adequacy. When implementation of large renewable energy source shares with fluctuating generation are introduced into the system, new kinds of flexibility measures are needed to balance mismatches between demand and supply (Kipping & Trømborg 2015; Lund et al. 2015).

One of these measures is to apply Demand Response (DR) into the system. Because of the great importance of electricity and space heating in the residential sector of Norway, electrical space heating as a DR measure can potentially act as a strong contribution to new flexibility into the power system which also increases the performance of capacity adequacy. If all electric radiators in a residential region was to raise the temperature setting some hours before the morning peak hour, a higher temperature increase than the normal temperature setting, all electric radiators could disconnect when the peak arise. This would potentially introduce a new large flexibility measure into the system (Vennemo et al. 2017b). When the radiators are disconnected, the envelope of the building body has retained the heat which now acts as a storage of energy, just like a battery. Under the peak hour, the thermal mass storage, because of thermal inertia, allows electric radiators and other electric equipment regarding space heating to stay disconnected while the storage of heat in the building body transmits back to surrounding environments. There are studies that document possibilities of minutes, even hours of this load shifting approach as a flexibility measure (Le Dréau & Heiselberg 2016; Reynders et al. 2017).

1.1 Motivation

As thermal mass is a well-known term considering thermal behavior of buildings, it is analyzed in several reports applying thermal mass capacity principles in different types of residential buildings or even national residential building stocks. Studies like Reynders et al. (2014a) show that thermal capacity can potentially be an important flexibility measure for future years. However, while this study is conducted in Belgium, which is situated in a milder climate than compared to Norway, it is known that how lower the temperature gets, larger loads of heating is needed, for example with direct electric heating. Thus, the load shifting demand potential increases in such a climate which makes Norway an ideal country to execute load shifting with electric loads. Norwegian residential buildings are generally very good insulated because of the cold climate. Most residential buildings in Norway is therefore good at retaining heat that has been heated with heating equipment. As the load shifting potential is generally high in cold climates heating with large amounts of direct electrical space heating, thermal mass in buildings becomes an important emphasis to increase the efficiency of a load shifting program. Nyholm et al. (2016) investigates the potential of electrical space heating in Swedish single-family dwellings to provide DR for the electricity load in Sweden. Nyholm et al. (2016) show that Sweden inhibits large potential in terms of thermal capacity in the Swedish residential building sector. Sweden which is situated in the same cold climate, Norway may also inhibit large potentials. While the Swedish residential sector has an overall electricity consumption amounting to 23% (Nyholm et al. 2016) and the Norwegian residential sector has an overall electricity consumption amounting to around 80% (Gaia 2011), would in principle make the potential in terms of flexibility larger in Norway per dwelling. According to Patronen et al. (2017), the electrical space heating and domestic hot water (DHW) heating amounted to 62 TWh in Norway in 2015 compared to 22 TWh in Sweden in 2016 (Patronen et al. 2017).

Reilly & Kinnane (2017) elaborates that there is a lack of research with focus on the performance of thermal mass in temperate and cold climates. This study analyzes thermal mass in a cold climate. Söder et al. (2018) implies that flexibility potential on the demand side is sparsely analyzed in Norway (Söder et al. 2018). According to my knowledge of literature research, this is the first time someone is calculating thermal mass in the form of effective heat capacity in the total Norwegian residential building stock and the first time this is compared to the electrical space heating demand potential in different segments of the building stock. Therefore, results of this thesis are a “kickoff” which can act as an encouragement to further study the vast potential of DR electric space heating with a thermal mass principle in use in the Norwegian residential building stock in future years. Vast untouched much needed flexibility in future years can be utilized if the topic of this thesis is analyzed and studied further in a Norwegian analysis. Thus, since the topic of this thesis is completely new in terms of Norwegian literature, it should be noted that the thesis is not a completed analyzed subject, rather a start of a long-based thorough analysis with accurate modelling considering thermal behavior of different segments and cohorts of the Norwegian residential building stock, sensitivity and economic analyses, political suggestions for a wide-based Norwegian DR integration system program etc. To my knowledge, this is also the first time someone is calculating load shifting potential in different segments of the Norwegian residential building stock in a period from 1960 to 2100.

1.2 Research objectives and research questions

The aim and goal of this thesis is to analyze and investigate the maximum potential of load shifting and delivered energy in the total Norwegian residential building stock quantified to different segments, building age classes and refurbishment states including usage of thermal energy storage in a demand response measure in the context of electrical space heating in Norwegian residential buildings quantified to the same segments in the stock in the period 1960-2100. In terms of the analysis of thermal mass, the thesis investigates the suitability of different building typologies through time for available thermal energy storage in the context of a demand response event. The goal is thereby to understand how different building segments in the Norwegian residential building stock with different thermal properties affect the potential for DR. The thesis will also analyze and investigate how and why a Norwegian wide-based demand response scheduling program may be integrated into the Norwegian power market in the future. In order to analyze the parts mentioned, the thesis use a building stock model developed by the PhD candidate Nina Holck Sandberg at NTNU. Data gathered from a building stock energy model also developed by Sandberg is also used to analyze and investigate the potential of electrical space heating and further used in the analysis of thermal mass. The building stock model is quantified into three segments, eight cohorts and three refurbishment states, which is also the case in the building energy stock model. Each modeled building means to represent a typical building of said type in the building stock. The thesis uses a social science approach, therefore use of engineering modeling are excluded from the thesis.

The research question is summarized as follows:

- *What is needed to implement a demand response scheduling program in the Norwegian power market?*
- *What is the maximum load shifting potential per segment in the Norwegian residential building stock in the period 1960 through 2100 concerning electrical heating in residential buildings in a demand response event?*
- *How will the potential of effective heat capacity change over time in different segments of the Norwegian residential building stock?*

1.3 Outline

The structure of the thesis is organized in seven main parts;

Part 1 gives a brief opener contextualizing the topic of the thesis.

Part 2 follows with a background chapter, to inform about important subjects regarding the main theme of the thesis. Flexibility, intermittent generation, demand response, thermal energy storage, energy use and space heating as an end-use activity is some of the topics presented and discussed in this part.

Part 3 is a presentation of the building stock model used in this thesis to conduct further analysis of the Norwegian residential building stock including result output from the period 1960 to 2100.

Part 4 represents the analysis regarding electricity use as space heating in the Norwegian residential building sector. The building stock energy model used, and method applied in the analysis is presented including assumptions and simplifications taken. Result output of different calculations is thereafter presented.

Part 5 represents the analysis regarding thermal energy storage in the Norwegian residential building sector. Method applied in the analysis is presented including assumptions and simplifications taken. Result output of thermal mass calculations is thereafter presented.

Part 6 aims at discussing the context of the thesis. Integration of DR, electricity use as space heating and use of thermal energy storage in Norway is discussed in this part.

Part 7 gives the conclusion of the thesis. Further work is suggested which can bring light to important insight in future analyses.

2 Background

The parts in this chapter will introduce information needed to comprehend the context of the thesis. 2.1 introduces the connection of why the need for new flexibility in the Nordic power region will increase in the future and what significance this has to Norway. 2.2 reviews available literature where DR is the focus. Firstly, possibilities of DR in Norway as a new untouched flexibility measure is outlaid and what significance this can bring to the need for flexibility in the future. Secondly, the literature review tackles challenges and barriers attached to overcome before fully operational DR can be implemented into a system. Lastly, the subchapter presents DR potential in both Norway and Sweden found in available present literature. 2.3 will give a brief introduction regarding thermal energy storage as a tool to improve the performance of a scheduled DR event in Norway. Important parameters and factors affecting the performance of the thermal mass in residential buildings is also presented in the subchapter. 2.4 presents past and ongoing trends in terms of energy use and space heating as an end-use activity in the Norwegian residential building sector including what has inflicted the efficiency of the energy use and what will affect the efficiency in the future going forward. Lastly, rebound and prebound effects in measurements of energy use is presented finishing chapter two.

2.1 Effect of intermittent generation increases the need for flexibility in a connected Nordic region

A Nordic power region which is distinguished as a unified, synchronous area with a common frequency (Statnett et al. 2016) stands above a transition to a system that includes large shares of renewables. The transformation of the Nordic power region is arising and it is expected that it will endure for a very long time (Bartelet et al. 2018a). Improved technology and decreasing costs have seen the growth in especially wind and to a lesser degree solar power penetration increase rapidly and substantially in the Nordic countries (Tveten et al. 2016b; Wiser et al. 2016). Looking at a global perspective, in the period between 2009 and 2014, solar and wind increased with 41% and 17% per year respectively (Söder et al. 2018). While technologies such as wind and solar power contribute to decarbonization, the primary energy source for these technologies however obtain a nature of behavior which consist of crucial characteristics that downgrades the technologies' value compared to other energy generating technologies. This is why these technologies has received their name "variable renewable energy" (VRE). Wind and solar power is variable, uncertain and location-specific (Tveten et al. 2016b). Variable because they are weather dependent, and thus the power output becomes variable. Uncertain because forecasting the primary energy is difficult and location-specific because certain locations are better suited than others concerning the generation. Past literature reviews find that variability is the most important characteristic. About two thirds of the VRE integration costs are caused by variability in supply of VRE (Hirth 2013; Hirth 2015; Tveten et al. 2016b; Ueckerdt et al. 2013), which cause an overall decrease in their market value because of the merit-order effect (Tveten et al. 2016b). However, VRE show significant signs that it will impact power markets in future years substantially. The International Energy Agency (IEA) use energy forecasts to provide insight for the future of the power system in the Nordic region concerning future energy use and efficiency in their Nordic Energy Technology Perspectives report from 2016. The forecasted future use of renewable energy in the Nordic region is projected through two energy outlook models which outlines different scenarios. IEA (2016a) reports that electricity generation in the Nordics today is already 87% carbon free. According to their Nordic Carbon-Neutral scenario, the power system will be fully decarbonized in the end of 2045, while their Nordic 4°C scenario shows a small amount of carbon technologies in the end of the same period. Wind generation in the Nordic power market will increase five-fold from 7% in 2013 to 30% in 2050 according to the Carbon-Neutral scenario. Furthermore, the model finds that the Nordic region will less likely see the severe solar generation increase which will occur in other parts of the world. IEA argue that solar power is limited in the Nordics because of dense urban areas with less rooftop area including more favorable conditions for competing wind, however IEA also argue that it is too early to rule out solar power completely (IEA 2016a). Because levelized costs of electricity for wind and solar technology are competitive and outperform some alternatives, they are highly expected to dominate capacity additions, especially after 2025. In the foreseeable future, along with closure of thermal power plants, it is decided that Swedish nuclear power plants will decommission earlier than initially planned, while Finland will step up their national nuclear program (Statnett et al. 2016). The composition of generation technologies in the Nordic power and heat system will go through a profound change because of large planned phase-outs of nuclear power including the forecasted rapid investment of wind power (IEA 2016a). The transformation also involves digitalization and automatization of the power system, which will lead to involvement of consumers to take part as active participants in the system. Evolution of information and communication technologies (ICT) has been introduced into the system with the installations of smart meters in Norway (Kipping & Trømborg 2016). Introduction and development of smart meters, microgrids and energy management systems can give the system flexibility to explore ways to regulate itself (Statnett et al. 2016).

Flexibility in a power market can be characterized as controllable parts of both production and consumption which is a valuable option to use when need of balancing (Kringstad et al. 2018; Statnett et al. 2016). Lund et al. (2015) describes flexibility as closely related to grid frequency, voltage control, production uncertainty and variability and power ramping rates. Huber et al. (2014) relates three metrics to define what is required as a flexibility measure. A flexibility measure needs some magnitude in terms of ramping. The response time is important including the frequency of the ramping (Huber et al. 2014). However, Lund et al. (2015) stresses, that defining flexibility in terms of a measure by chosen metrics may be unambiguous for different definitions, because of the complexness of an energy system. A single or few indicators to indicate the performance of flexibility of a measure can therefore be inaccurate.

While low average generation costs in the Nordic region has been a trend, greater integration with continental Europe will likely see changes to Nordic electricity prices. Due to high demand, increased interconnection between the higher price regime in continental Europe and larger shares of variable renewables introduced to the system, an effect of increased price volatility will occur more frequently in the Norwegian and Nordic market in the future (IEA 2016a; Kringstad et al. 2018). However, with increasing transmission capacity and a positive power balance within the Nordic power market it may reduce the effect of price volatility in each bidding zone. Due to the complex situation of different factors effecting future price volatility dissimilar, the future of Norwegian electricity prices are to some degree uncertain (Fiksen et al. 2014). If no major technological development in large-scale long-term storage occur in the future years to come, effect of increased price volatility will develop increasing need for other flexibility measures in the system (Kringstad et al. 2018). Pointed out by Fiksen et al. (2014b), the willingness to pay for flexibility varies across time and space in terms of type and quantity of flexibility. Long-term, both demand and supply side fluctuate because of economics, technology and politics. Due to differences in a generation mix and pattern of consumption across time and space, a variety of different flexibility measures are needed geographically and to enable transactions in terms of flexibility between price regions (Fiksen et al. 2014). With a flexible system, costs of integrating high renewable energy market shares may reduce (Tveten et al. 2016b). While larger amounts of VRE is introduced into the system, the need of flexibility increases parallelly, which could be achieved by applying different flexibility measures (Lund et al. 2015). As Norden (2015) so nicely put it: “the demand for flexibility in the system increases, while the supply of flexibility decreases”.

Various approaches can be adopted to increase system flexibility, both at demand and supply side. One way of increasing flexibility is merely strengthen the power grid which enables better spatial smoothing in the system, but is generally perceived as an expensive measure (Scorah et al. 2012). Storage, as discussed earlier, has also received attention as a valuable measure (Lund et al. 2015). While storage is recognized as suitable combined with renewable energy (Paatero & Lund 2005), it is also often distinguished as a bit optimistic in terms of a flexibility measure because scale of energy is often underestimated (Converse 2012). DR is another potential flexibility measure which can lead to major reorganization of the Norwegian power system (Kringstad et al. 2018). DR which is the focus of this thesis is discussed further in subchapter 2.2. In addition to DR, development of Smart Grids and ICT into the system shows a great potential for better handling and performance of a power system (Fang et al. 2012). Norway already have large amounts of available flexibility in terms of regulated hydropower, however Kringstad et al. (2018) stresses that the reservoirs are not inexhaustible and therefore more and different flexibility measures will be needed in the future. Transition to a renewable complex interconnected flexible Nordic power market has already begun. The system transformation will change how we use energy and how we respond to the ever-changing price signals.

2.2 Possibilities, challenges and barriers related to demand response: Literature review

DR is defined as *“the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time”*. It also can be defined as *“to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”* (Albadi & El-Saadany 2008; Siano 2014). DR is an objective to deploy consumer-based flexibility into an energy system.

Several reports have stated that large potential in Norway exist today, which can provide considerable quantity of needed flexibility into the Norwegian power market in future years. DR has potential to make a substantial impact on how the power market will be operated in future years with a push of some of the regulating control generators exhibits in terms of flexibility over to consumers, especially in peak periods (Fiksen et al. 2014; Kringstad et al. 2018; Vennemo et al. 2017a). DR is also a valuable option to increase performance of capacity adequacy in power markets (Söder et al. 2018) and enabling of price sensitive end-use through DR can prove upon price formation in the market. With increased VRE generation, the price will develop with more volatility, as discussed earlier. With development of DR, it can dampen the effect of very high prices in peak load hours. In the power market today, generators and some large consumers provide the present flexibility for system services. But at geographical locations in Norway where flexibility is crucial for system services, end users may be the only provider in some areas and can provide crucial flexibility in these areas. Areas dominated by stored hydro, flexibility is abundant. In areas due to domination of wind power, households can provide much needed flexibility (Fiksen et al. 2014). DR, is according to Albadi & El-Saadany (2008), one of the cheaper resources available for operating the power market (Albadi & El-Saadany 2008). Because, the energy usage has not been monitored before of late, consumers have not had the possibility to be rewarded for reducing consumption. However, smart meters also called Advanced Metering Systems have now been rolled out for all Norwegian residential consumers. With the installation of smart meters, consumers now have the ability to be provided with real-time information about their own consumption and marginal prices. The problem of consumers not exposed to real-time pricing are now eliminated after incorporation of smart meters, which have the possibility to increase demand flexibility (Bolkesjø et al. 1996).

Vennemo et al. (2017a) believes that the installation of smart meters and other automated equipment can potentially impact the demand of electricity and shifting of electricity loads, especially if these appliances are incorporated into a Norwegian wide-based development system of DR. These appliances will then contribute as essential parts of a Norwegian DR program in the future including all end-users as participants. ICT and automation are also a crucial part of enabling demand flexibility. It assists consumers respond to price signals. Full automation would allow connecting and disconnecting of equipment in response to the price signals. As Vennemo et al. (2017a) implies, no consumer would be able to connect and disconnect according to the price signals manually. ICT and automation are therefore seen as a crucial part to reduce transaction costs and barriers of demand flexibility and to increase price elasticity of demand (Vennemo et al. 2017a).

The providing flexibility of DR has certain characteristics which enables the desired effect in a system. Load shifting capability, volume and various time aspects as for example duration, response and recovery time as well as the reliability of delivery determine how well a DR measure perform during an event (Fiksen et al. 2014). To be able to apply fully operational DR into a system, Fiksen et al. (2014b) emphasizes that a demand for flexibility has to be in place including that the flexibility has to be able to compete with other flexibility measures in the market, discussed in the last subchapter. By this note, Fiksen et al. (2014b) stresses that the demand side must be able to deliver the valued characteristics of flexibility mentioned above in a cost-efficient manner. The main action of present DR is normally concerning disconnection of loads but providing the full potential of flexibility means that end users is also available to connect or increase loads (Fiksen et al. 2014). Time-based and incentive-based programs are DR measures that exist today, however due to various barriers such as technical, economic, legal and societal, use of DR measures are fairly limited at present time. Programs that are operating today are generally focusing on large industrial consumers (Gils 2014). Today, there are few examples of electricity system operators that have tried to control demand use in terms of electrical heating as part of DR efforts. However, it has been shown in countries such as Germany, New Zealand, US and UK that electric heating as a DR measure has been achieved providing compelling effects with comparatively uncomplicated control and communications (Bartelet et al. 2018b).

The demand sector composed of residential, commercial and industrial segments (Gils 2014), bear fairly different end use patterns compared to each other. Considering a weekly load curve, industrial end use of electricity is far more stable than of a residential which maintain a more variable behavior. How responsive residential demand is to price changes is a key issue to development of DR. The residential sector which is the focus of this thesis is the only sector which will be discussed further. Vennemo et al. (2017a) lists a variety of factors that the demand of electricity in the residential segment depends upon:

- *Outside temperature*
- *Household income*
- *Household size and composition by age and gender*
- *Consumption patterns due to work hours, weekends and holidays*
- *Location of dwelling*
- *Dwelling structure characteristics*
- *Fuel substitution*
- *Electricity price structure and the variation of prices over time*
- *How informed the consumers are about prices*
- *Technical solutions and ICT that reduce transaction costs and facilitate DR in response to price*

Outside temperature is acknowledged as one of the more important factors contributing to residential electricity demand. If the temperature decreases, comparatively the electricity demand for space heating will increase. Household income effects how much electricity is used in cold winter periods. The larger the size of a household is, generally more heating is required in terms of delivered electricity intensity per square meter. Composition of age and gender including how many persons living in the household has an effect on the inside temperature due to a set of factors, two of them being the tolerance for a specific temperature level and internal heat gain contribution from number of people and equipment which transmits heat. Residential consumption pattern during for example work hours has large infliction on the demand load curve, decreasing the load during these hours. Location of dwelling is of importance in terms of for example different climate regimes effecting the need for heating. Dwelling structure characteristics has large infliction on how much heat a building can retain, due to for example U-values set in different technical building regulations. The electricity price structure and variation of prices over time effect the electricity usage. In high price periods, some fuel substitution to wood burning stoves are normal. How informed the consumers are about the prices inflicts different parts of the residential sector (Vennemo et al. 2017a). Technical solutions and ICT is discussed later in the thesis. Concerning residential consumers, in the report Demand side flexibility in the Nordic electricity market conducted by Norden (2017), DR measures at household level has been quantified into five main categories:

- *Heating and cooling system*
- *Household appliances*
- *Local generation of electricity, like photovoltaic (PV) systems*
- *Local storage, hot water or electricity (batteries)*
- *Transportation, i.e. electrical vehicle (EV) charging*

Darby & McKenna (2012) lists available programs which is used for DR (Darby & McKenna 2012):

- *Energy efficiency and conservation programs:* encourage participants to conserve or be more efficient in terms of energy usage over a longer period, which reduces overall demand.
- *Static time-of-use pricing:* electricity prices vary throughout the day and when demand is low (at night) prices are low and vice versa (during the day).
- *Critical day pricing:* similar to static time-of-use but where prices are higher, throughout the day, on a “critical” day compared to a non-critical day.
- *Peak time rebates:* consumers receive rebate if use is below a given threshold in a critical peak period. Similar to critical peak pricing.
- *Real-time pricing:* electricity prices vary throughout the day, generally hourly.

- *Demand-side bidding:* consumers participate directly in the electricity market. Demand side bid for expected use. Typically, automated by end-use appliances.
- *Dynamic demand:* automated appliances switch off when frequency drops.

DR consist of three quantifiable measures that comprises which means customers have the ability to use during a scheduled event lasting for minutes or some hours at maximum in terms of electricity usage (Fiksen et al. 2014). All measures lead to a desired reduction of peaks in a load curve (Kringstad et al. 2018):

- *Shut down of energy use*: the demand side decrease their load when a peak in the load curve appears without changing the consumption pattern during other periods, overall consumption is reduced. This type of measure will lead to a loss of comfort (Fiksen et al. 2014).
- *Shift to an alternative type of energy source*: the demand side have the ability to switch the type of energy source. For example, direct electric space heating is replaced by biomass in a household (Fiksen et al. 2014).

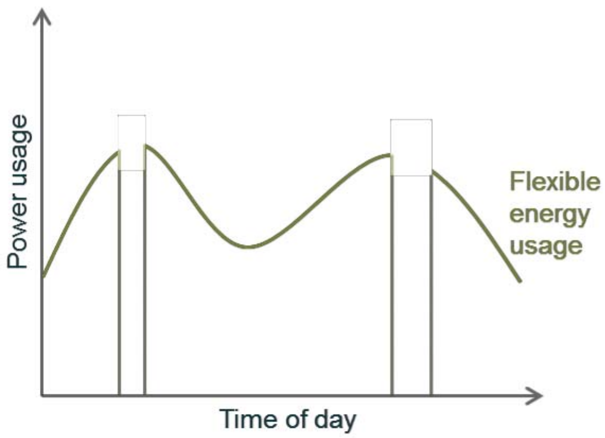


Figure 1: Effect on load curve by shut down of energy use or shift to an alternative type of energy source. From Fiksen et al. (2014b).

- *Load shifting*: load generated in peak hours becomes redistributed to low demand hours. The impact is that the peak hour decreases while the load in low load hours increase, enabling smoothening of the load curve over time. This implies no reduction in energy consumption. Consumption in peak hours in the morning is moved to the night before the morning as an example. Space heating and water heaters, along with household appliances is technologies that relatively easy can be shifted without significant loss of comfort (Vennemo et al. 2017a).

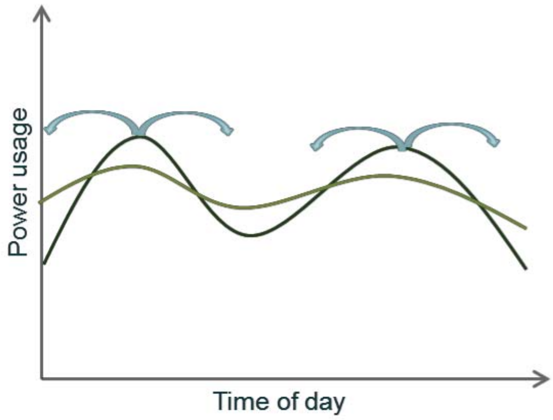


Figure 2: Effect on load curve by load shifting. From Fiksen et al. (2014b).

With these measures contributing to an energy system, consumers are able to apply added flexibility to the load curve. Lund et al. (2015) argue that load shifting is beneficial when comparing it to the other measures, because it allows to apply flexibility without compromising continuity of the process or quality of the measure. Lund et al. (2015) emphasizes that, while energy storage has the same functionality as load shifting, the difference is that load shifting can provide the service with 100% efficiency, as it does not require conversion from an intermediate storable form. Load shifting is the measure that is considered, when applying the thermal mass principle in this thesis.

2.2.1 Challenges and existing barriers and impact of elimination

In literature, there is evidence that consumers which manage their own loads has difficulty to recognize how to act as a responsive consumer in terms of the power market. Fiksen et al. (2014a) addresses that this type of consumer does not understand the difference between power and energy. This, according to the authors, leads to a general reduction in energy consumption rather than moving power loads in time. Vennemo et al. (2017a) addresses that this type of consumer also does not know at which times of the day prices are high. Vennemo et al. (2017a) argues that barriers and obstacles remain, which can be related to the design of real time prices, interaction between pricing signals and regulation of distribution grid operators and role of aggregation of small consumers as some examples (Vennemo et al. 2017a). Vennemo et al. (2017a) conducts a study of existing barriers of development of DR, and what the impacts will be if these barriers are removed. In the following part, these barriers will be reviewed. All barriers are commented below I-V. In each comment, a list of pros and cons is attached as it represents impacts each barrier will have if they are to be removed. I-III considers retail and grid/Distribution System Operator (DSO) side and IV-V considers wholesale side.

Existing barriers preventing full deployment of DR is as follows:

- *(I) Real-time pricing and metering*
- *(II) A market for aggregator services*
- *(III) ICT and automation services*
- *(IV) A shorter settlement period*
- *(V) A lower minimum bid size*

I: Real time pricing and metering

<table>
<tr><td colspan="2">Real-time pricing and smart meters are seen as the key barriers to overcome. It enables correct information so that consumers or by an aggregator service responds to price signals swift and accurate. By employment of smart meters fully equipped in the Norwegian residential segment, Vennemo et al. (2017a) urge to therefore turn the attention to the price structure, which according to the authors are not fully developed in terms of DR (Vennemo et al. 2017a).</td></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>- Exposes scarcity in the power market
- May lead to better allocation of resources
- May lead to decreased grid investments</td><td>- Volatility of prices may create consumer uncertainty (II can overcome the problem)
- As real-time-pricing must reflect both production and grid scarcity, if not precisely designed, it can ill inform consumers
- Installing smart meters has been costly, leading to a “sunk” cost if not used as a DR component</td></tr>
</table>

II: A market for aggregator services

<table>
<tr><td colspan="2">Aggregation services are services which take control of some or all appliances to small consumers. A mental cost in terms of opportunity cost has to be considered if individual consumers want to take control of their own load with hourly changing power prices while at the same time give assurance to the grid company that for example the consumption really will be reduced when the need arrives. Aggregation services will be in control and coordination of optimal aggregation, both in wholesale and retail or in terms of selling services to TSOs. Aggregation services can improve upon more efficient management of transaction costs for consumers and avoid risk of demand exceeding supply during peak periods. Services can offer consumers a discount in return of control (Darby 2018; Vennemo et al. 2017a).</td></tr>
<tr><th>Pro</th><th>Cons</th></tr>
<tr><td>- Will improve response to price signals
- May lead to better allocation of resources
- May lead to decreased grid investments
- May improve utilization of VRE</td><td>- If a grid company enters aggregation services, basic distinction between production and grid will be challenged
- As current revenue regulation works, DSOs/TSOs can pass on the cost of investing in grids. Incentives to invest in alternatives to networks is thus limited
- Loss of personal control matter of concern for some (Darby 2018)</td></tr>
</table>

III: ICT and automation services

ICT and automation services will give added accuracy to real-time pricing and the operation of the power market. These services can act as an important extension to be able to compose the most accurate information available for both consumers, aggregators and generators (Vennemo et al. 2017a).	
Pros	Cons
- Will improve response to price signals and scarcity - May lead to decreased grid investments - May lead to better allocation of resources	- Personal privacy may be intervened

IV: A shorter settlement period

To be able to shorten the settlement period in the power market from 60 minutes to 15 minutes will according to Vennemo et al. (2017a) allow the market to track scarcity more accurate and on a more continuous basis. This will eventually reduce a barrier.	
Pro	Cons
- Facilitate better coordination between prices and underlying scarcity	- Will require costly upgrade of control equipment and ICT infrastructure for operators and participants

V: A lower minimum bid size

Because of the bid size in the Norwegian power market, smaller participants are excluded from the operation, which may exclude most of the potential in the residential sector, especially for individual consumers which offer flexibility with a small quantity. Lower minimum bid size will similarly to shortening of the settlement period make the market more accurate and to track peaks in the load with higher accuracy. Nordic wholesale markets have rules of 5-10 MW and 60-minute resolution which is unfavorable for smaller consumers to participate in a DR program.	
Pros	Cons
- Lower the barrier for entry - Facilitate better functional market - Will provide better allocation of resources - Will decrease grid investments	- Manual operation difficult to achieve - Large potential of smaller consumers, which require ICT systems to handle large quantities of traffic which today standard of ICT cannot handle - More difficult to maintain ICT security

Of the five recognized barriers, Vennemo et al. (2017a) identifies real-time pricing and metering as the most important feature which operates as the foundation of development of DR. Both number II and III will be of less importance if number I is not provided. The authors elaborate that the measures I-V are set in the order from most important to least important. For example, introduction of aggregator services will not develop if implementation of real-time price structure with metering is not achieved (Vennemo et al. 2017a).

2.2.2 Review of technical and economic potential of DR in the Nordics

This chapter will give a short summary of what literature can say about what the technical and economic potential of DR is today among studies analyzing this topic. When analyzing technical and economic potential there is important to distinguish between the two categories including theoretical and practical potential. COWI (2016) defines theoretical potential as *"all facilities and devices of the consumers suitable for demand response"*. However, with a theoretical potential, the maximum amount of what is estimated as the potential will most likely not materialize in a real situation as it is only theoretical. Technical potential is regarded as the only facilities and devices of the theoretical potential that can be managed by existing ICT. The economic potential can be extracted as the summarized achievable cost-efficient measures from the technical potential. The economic potential is always smaller than the technical. The actual deployment of DR is regarded as the practical potential that is the part of the economic potential that is accepted by users (COWI 2016). It is also important to keep in mind that estimates reported in different studies have been conducted in different time periods or with fairly different assumptions effecting the outcome. For example, the change of share in VRE are rapid and, thus studies reporting the penetration of VRE will vary over time. Investments in the grid will also vary leading to the same variation in estimated output. With this in mind, reported economic and technical potentials can have large variations. Regardless, there is interesting to have some form of knowledge about what have been conducted to this point in time. Practical potential is not represented in this thesis since it is difficult to know the exact quantity of what is accepted by users. Therefore, following reports and studies contains technical and economic potential only. These reports and studies are:

- Nyholm et al. (2016): assesses DR potential of electrical space heating in Swedish single family dwellings. 571 sample buildings representing single family dwellings are modelled, which is applied to 1.29 million Swedish dwellings. Heated floor area used is 192 million m^2. Effective heat capacity of each building used in the work is a fixed value per square meter of the buildings' heated floor area which is amounted to be 36.1 Wh/m^2K. The study shows that technical potential in the Swedish residential sector are 5.5 GW in the winter period concerning only space heating. The potential for spring, summer and fall are lower (Nyholm et al. 2016).
- Puranik (2014): conducts a master thesis of DR potential for Swedish residential households in terms of dishwasher, laundry and water heating loads. The thesis investigates the potential for DR in the form of load shifting of residential electrical loads in Swedish households. Total load reduction in an observed winter week was around 300 MW, and load addition of around 2-3 GW in off-peak hours of a day in the week. A week in spring follows the same pattern with load reduction. Daily shifting potential for Swedish single family houses with use of washing machines, dishwashers and dryers show a result of 8-9 GWh a day in a week wintertime and 3.3-5 GWh springtime and 0.8-2.7 GWh a day in a weekend wintertime and 0-3.7 GWh springtime (Puranik 2014).
- Sæle & Grande (2011): conducts a pilot study focusing on daily DR potential of electrical water heaters in Norwegian households. The results show a DR potential of 1

kWh/h for consumers with electrical water heaters. Potential for DR from 50% of Norwegian households is estimated to be 1000 MWh/h (Sæle & Grande 2011).

- Gaia (2011): conducts a study of the combined DR potential in the Nordic countries. Figure 3 show the result output from the study. DR potential is based on the share of electrical heated homes and estimated volumes per house. 80% of Norwegian households are electrically heated compared to 50% and 6% in Sweden and Denmark according to the authors. Nordic electrical heated homes have each a potential of switching 1-2 kW from peak hours to off-peak hours. It shows that most of the flexibility potential are situated in Norway and Sweden, while especially Denmark show a fraction of that potential. Norwegian households possess a potential between roughly 1 GW and 3 GW. The potential output varies more compared to Swedish households which possess a stable 2 GW. The potential outputs in the study are identified by the authors as uncertain which has technical, economical and practical barriers (Gaia 2011).

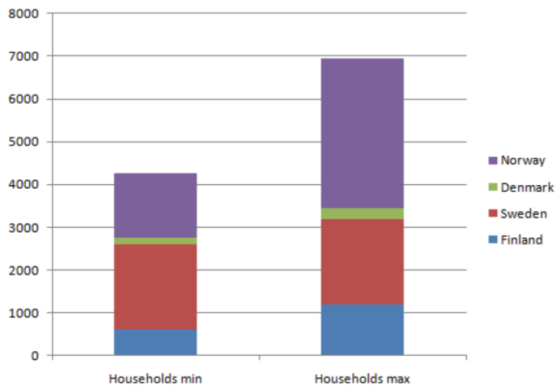


Figure 3: Results of Gaia (2011) in terms of DR potential (in MW) in the residential sector concerning space heating. From Gaia (2011).

- Meland et al. (2006): conducts a report of available DR potential in Norway. 70% of electrical space heating in Norwegian residential dwellings as the main heating source is used, while 70% of the dwellings also have a secondary heating source with a woodstove. A roughly estimated result output shows a DR potential with substitution in a normal year of 2-3 TWh in the residential sector (Meland et al. 2006).
- Gils (2014): conducts a study which assess the theoretical potential in Europe. Result output from Norway show that average potential for load increase by shifting to an earlier point in time is roughly 5.9 GW considering only residential storage heating (Gils 2014).

- Kringstad et al. (2018): conducts a report of flexibility in Norway. A roughly estimated load shifting potential in space heating in Norwegian residential buildings in a Norwegian peak hour based on (Havskjold 2017) to be roughly 4.1 GW, however some of this potential is hard to achieve and the economic potential is derived to be roughly 1.8 GW. Most of the economic potential in the residential segment has a time period of less than three hours (Kringstad et al. 2018). Figure 4 show an average week of BID load shifting simulations in 2030 in east Norway conducted by Kringstad et al. (2018). Positive quantity means increase in demand in terms of the profile used.

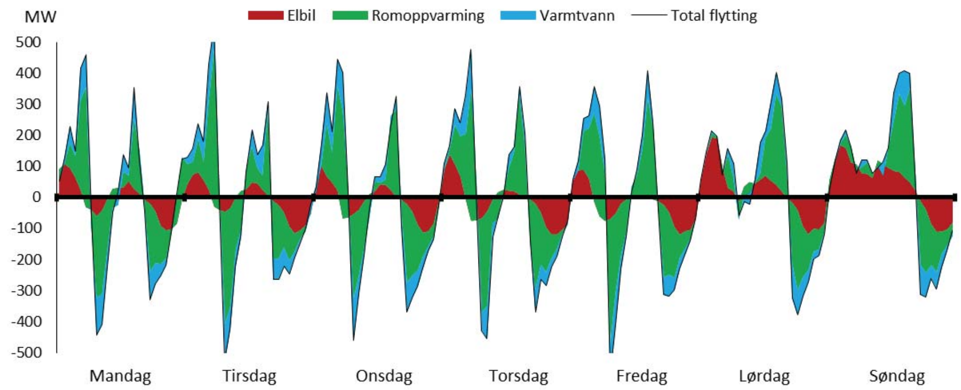


Figure 4: Results from Kringstad et al. (2018) of average load shifting (in MW) in a week in 2030 in East Norway. BID-simulations with flexible demand. Electric vehicles (red), space heating (green), DHW (blue), total shift (line). Text in Norwegian. From Kringstad et al. (2018).

- By the use of calculations in Nyholm et al. (2016) and assuming proportionality between Swedish and Norwegian consumption and maximum load shift, Vennemo et al. (2017a) estimates a potential of 20 GW for all energy consumption in buildings. But the authors indicate that aggregated loads in the transmission grid in terms of maximum load that can be shifted will not be as large as 20 GW.

Heating and cooling system has been considered as the most promising category along with potential storage of electricity in batteries and hot water as DR measures (Norden 2017). Kringstad et al. (2018) indicates that DR in the Nordic region has vast technical potential and argues that smart meters including smart home technology makes the applicability of dwellings easier to adapt to changing power prices including using electricity in a smarter way (Kringstad et al. 2018). In the work of Vennemo et al. (2017a), it is found that space heating offers the highest potential in residential buildings in terms of DR. The authors found that residential space heating contributes with at least half of the total potential according to studies conducted in Sweden, Germany and other parts of Europe. The authors found that residential space heating is especially suited for hour-to-hour flexibility (Vennemo et al. 2017a). The flexibility implies that equipment must be turned up at night and down in the morning (Vennemo et al. 2017a). Kringstad et al. (2018) implies that self-owned solar power production and battery storage can potentially have an effect on future peak load curve hours decreasing peaks and high price hours. Potential of DR is higher in the residential sector compared to the industry according to the reports of Vennemo et al. (2017a), Lund et al. (2015), Nyholm et al. (2016) and Gils (2014). Large quantity of technical potential exists in the Swedish single family house segment with electric heating and the potential is available during a period from 1-3 hours (Alvehag et al. 2017).

2.3 Infliction of thermal energy storage in a DR event with electrical equipment

Thermal energy storage (TES) is defined as a *"device that can store thermal energy by cooling, heating, melting, solidifying or vaporizing a material"*. As this thesis only focusses on the concept of heating, this will only be reviewed. In literature, there are common to quantify three types of TES systems (Arteconi et al. 2012; Dincer 2002). By the use of:

- *Sensible heat*: storage in materials in which the temperature rises or falls
- *Latent heat*: storage in materials which undergo phase changes
- *Thermochemical heat*: storage in materials with inorganic substances which is based on a reversible chemical reaction

Studies that focuses on TES by using an approach of latent heat contains the use of phase change materials (PCMs) (Kheradmand et al. 2016; Pomianowski et al. 2012; Thiele et al. 2017). Studies investigating PCMs has been an important part of the learning process of building performance using TES, which can offer high thermal storage density (Zhou et al. 2012). A review of literature containing use of PCMs, Zhou et al. (2012) found that a large extent of these studies found that indoor temperature fluctuations can be reduced significantly whilst maintaining desirable thermal comfort. Use of thermochemical heat in materials in the field of building performance in terms of TES has been researched to a lesser degree compared to the other approaches, but has caught attention in the field of research lately (Aydin et al. 2015). While this thesis focusses on sensible heat solely, latent heat and thermochemical heat are excluded from the thesis, despite showing large potential.

There is extensive amount of studies which investigates thermal energy storage (TES) as a flexibility measure instigated as a space heating DR event in the residential segment (Brahman et al. 2015; Le Dréau & Heiselberg 2016; Patteeuw et al. 2015; Reynders et al. 2017). There is studies that focuses fully on district heating systems (DH) as the energy supply under a DR event (Kensby et al. 2015; Skari 2016) or electrical heating with or without heat pumps (HPs) (Ali et al. 2014; Alimohammadisagvand et al. 2016; Wolisz et al. 2013). Consensus in literature acknowledges that using TES in DR is a promising, efficient and economically viable technology which not only can deliver flexibility but also enables a wide-spread integration of efficient VRE generation to a system (Dominković et al. 2018; Navarro et al. 2016; Reynders et al. 2014). As Dominković et al. (2018) implies, there are no physical alterations to consider in buildings which enables the DR measure as a low cost measure. Navarro et al. (2016a) elaborates that TES can also improve relability of performance of space heating and consitutes less pollution for example in the form of CO_2 emissions. However, according to Reilly & Kinnane (2017), there are few studies which analyzes TES in a generalizable, quantifiable sense. The authors argue that most of the studies aims to show the positive sides of thermal mass. However, they argue further that it can be a sense of hindrance, which can be confusing or simply wrong in terms of the benefit of thermal mass. Effects of thermal mass is defined by the authors as subtler and more dependent on wider range of factors than the effects of resistance. For example, occupancy patterns, external temperature profiles, average temperature and details of wall constructions. Authors points out that thermal resistance is easier quantified to a model, whereas impact of thermal mass is far more difficult and time consuming to model (transient numerical analysis or analytically complex methods). A drawback is that quantifying the dynamic properties of thermal mass lacks a single parameter. It constitutes numerous parameters that influence each other (Reilly & Kinnane 2017).

Reynders (2015) defines a DR event as *"an active, temporary deviation from normal behavior without violating comfort requirements"*. The basic principle of TES with sensible heat is that energy is charged, stored and discharged for later use in a material based on an increase and decrease of temperature in the surrounding environment. The amount of heat that can be stored during a DR event is limited by the temperature variations in a building and thus depends on the comfort requirements set by consumers. Thermal properties of the building like insulation has large infliction on how a building perform during a DR event including how efficient the heating system is. Heat is gained through technical equipment, lighting and from people themselves indoor (Høseggen 2008). The occupant behavior is a factor that is recognized as a major influencer to uncertainty concerning building performance (Yan et al. 2015). However, climatic conditions are the most influential factor deciding the amount of heat that can be stored at specific points in time. Air temperature throughout a building depends largely on the outdoor temperature including solar radiation. Temperature indoor variates through a day, where a peak typically occurs at early afternoon when the outdoor temperature reaches its highest point of the day, the sun is lower on the horizon and when the building has been in use for some hours of the day (Høseggen 2008). In a building, figure 5 show how heat are transferred and distributed by convection (forced or natural), by radiation (short-wave or long-wave) and by conduction. The figure clearly shows the complexness of the dynamic behavior of heat transfer processes. Høseggen (2008) points out that the figure show heat transfer processes before heat gain from occupant behavior are considered which will complicate the output further. To calculate the resulting indoor temperature, computer models are generally used (Høseggen 2008).

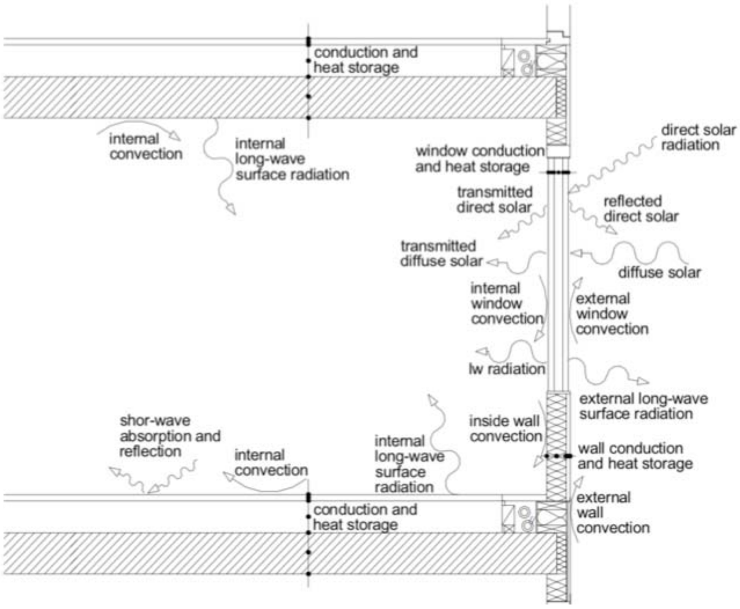


Figure 5: Cross section of the envelope of a residential building showing heat transfer processes. From Høseggen (2008).

There exists a total of three types of contributions on how thermal mass can be stored in a building:

- The envelope and structural elements (Interior walls, ceilings and floors, including some main bearing materials)
- The air volume
- The fittings, furniture and other objects (Høseggen 2008)

The term interior is used as the inner layer prior to a building structure's inside air. Whether it is used to describe inner layers of walls, ceilings or floors, the meaning of the term-use is the same throughout the whole thesis. The envelope and structural elements dominate as the most important objects for thermal storage. Contribution from air, fittings, furniture and other objects is just a small fraction compared to the potential in the envelope and structural elements and are thus not considered in this thesis.

The principle of TES in a building can be illustrated by a single power node. In figure 6, Heussen et al. (2012), illustrates how an energy storage can act as a buffer between external processes ξ and two grid-related exchanges, *ugen* and *uload*. TES can provide a capacity *C*, between a level of $0 \leq x \leq 1$. The capacity is affected by internal energy losses in a TES by $v \geq 0$ and enforced energy losses which is denoted by a waste term *w*, quantified by a loss of provided energy $w > 0$ and unserved load $w < 0$ (Heussen et al. 2012). The amount of energy that is stored in the form of heat in all materials in a building is proportional to the density (ρ) [kg/m^3] which refers to the mass per unit volume and thickness (*d*) [mm] of the specific material including specific heat capacity of the material (c_p) [J/kgK] which is the amount of heat that is needed to raise the temperature of 1 kg of the material by 1 degree (Høseggen 2008). Total heat capacity can be calculated as the sum of heat capacity in each layer *i*, i.e.:

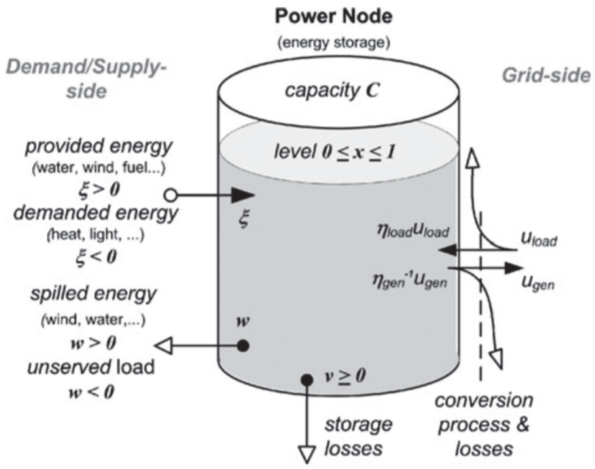


Figure 6: Representation of a "power node". From Heussen et al. (2012).

$$C_T = \sum_n d_i \rho_i c_{p,i} \quad (\text{J/m}^2\ \text{K})$$

Thermal inertia of different building materials can also be determined by effective heat capacity. As the capacity of TES as a system is subject to variable boundary conditions, the "real" potential of TES are variable for different building types and cohorts in the residential building stock utilizing different interior materials in walls, floors and ceilings in contact with the indoor air (Vennemo et al. 2017a). Vennemo et al. (2017a) describes effective heat capacity as the quantifiable *"heat capacity that is actually in use for a specific purpose, within given limitations"*. Effective heat capacity is a number determined by a set of assumptions to generalize and quantify effective heat capacity for a range of different materials. Heat capacity is determined by nodal temperatures, while effective heat capacity is determined by an assumption of temperature variation across an element and is therefore more accurate. In this thesis effective heat capacity is used as the parameter to calculate TES. Table 1 show effective heat capacity for different materials used in a building (Programbyggerne n.d.).

Table 1: Effective heat capacity for chosen constructions. From Programbyggerne (n.d.).

Construction	Effective heat capacity (Wh/m^2K)
"Homogeneous" constructions	
Concrete, thickness> 102 mm	63
Brick, thickness> 81 mm	59
Light clinker, thickness> 64 mm	14
Compact wood (lift / plank); thickness> 39 mm	12
Bonding / joints / ceiling	
Interior cladding: 12 mm plasterboard	2
Interior cladding: 12 mm chipboard	3
Interior cladding: 15 mm wood panel	5
Interior cladding: 21 mm floor board	6
Interior cladding: 22 mm chipboard (floor)	6
Covered heavy constructions	
Thin carpet (5 mm) on concrete deck	38
Thick carpet (10 mm) on concrete deck	19
Parquet (14 mm) on concrete deck	35
"Open" suspended ceiling under concrete deck	30
"Dense" suspended ceiling under concrete deck	10

However, how much thermal mass which is usable under a DR event is also decided by a range of other parameters and terms which influence the complexness of TES. Following parameters and terms effects the performance of TES in a building:

- Thermal conductivity (λ) [W/mK]: is the performance of how effective a material is to conduct heat. Al-Homoud (2004) defines λ as the *"time rate of steady state heat flow (W) through a unit area of 1m thick homogeneous material in a direction perpendicular to isothermal planes, induced by a unit (1 K) temperature difference across the sample"*. The main form of heat transfer through materials in buildings is conduction. Lower number results in slower conduction. Thermal conductivity is also known as the *k-value* (Al-Homoud 2004). It is worth to mention that when calculating thermal conductivity, assumptions are made about the extent of the thermally active volumes of a material including that it ignores the effect of the period over which heat is absorbed and emitted from the material (Lymath 2015).

- Thermal resistance (*R-value*) [m^2K/W]: is how resistant a material is to heat of energy passing through it in terms of conduction, convection and radiation and is a function of a material' thermal conductivity, thickness and density. If a material possesses high thermal resistance, it is described as a good insulator and bad insulator vice versa. The *R-value* can also be derived by the thickness of a material divided by λ (Al-Homoud 2004).
- Thermal insulation: Al-Homoud (2008) defines it as *"a material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection, and radiation"*.
- Thermal transmittance (*U-value*) [W/m^2K]: Al-Homoud (2004) defines it as the *"rate of heat flow through a unit surface area of a component with unit (1K) temperature difference between the surfaces of the two sides of the component"*. It is the reciprocal of thermal resistance (Al-Homoud 2004).
- Thermal admittance (*Y-value*) [W/m^2K]: Al-Homoud (2004) defines the admittance of a material as *"its ability to exchange heat with the environment when subjected to cyclic variations in temperature"*.
- Thermal diffusivity (κ) [m^2/s]: Høseggen (2008) defines it as *"how fast a heat wave travels through a material"*.
- Thermal effusivity (β) [$Ws^{1/2}/(m^2K)$]: also called the heat penetration coefficient. According to Høseggen (2008), materials with a high coefficient will more readily absorb a surface heat flux compared to other materials with a lower value.
- Decrement delay: also called thermal buffering, which is measured in hours, is defined by de Saulles (2012) as *"the time lag for heat to pass through a material"* (de Saulles 2012).
- Diurnal heat flow: de Saulles (2012) defines it as *"the heat that flows to and from a building or space over the course of 24 hours"*.

Appendix 1 shows a set of parameters concerning thermal behavior for some materials. Due to simplicity of calculations estimated in this thesis, only effective heat capacity is determined to calculate the total amount of thermal mass in partitions. Effective heat capacity integrates some of the parameters presented in the part over, but with a one-single parameter it is difficult to determine the total capacity of a partition fully accurate. Engineer modeling is required to fully interpret the thermal behavior inside a building but is not conducted in this thesis since it is a social science study. However, the one-single parameter can give a fairly correct result of a large sample that is the complete Norwegian residential building sector.

Høseggen (2008) points out that the order of the materials influences the performance. All materials in buildings perform differently in terms of TES. Heavy buildings commonly equipped with heavier materials like concrete have an ability of high thermal capacity. Buildings equipped with more lightweight materials like timber or gypsum has a lower potential of thermal capacity. How the materials are layered in walls, ceilings and floors have a significant effect of how much thermal mass can be stored in the respective materials (Vennemo et al. 2017a). The most effective depth of a material is the first 50 mm. Between 50 mm and 100 mm, the material loses some of the potential to store thermal mass. Beyond 100 mm, the potential is largely inconsistent (Lymath 2015). Insulation has a large effect on thermal capacity because the intention to insulate is to reduce the rate of heat transfer, thus limiting the potential of thermal capacity. If a wall is insulated on the side facing the indoor air, even though materials beyond the insulation has large thermal capacity, the wall cannot utilize the potential of large thermal capacity because insulation is "clogging". Therefore, using materials with high thermal capacity as outermost material to the inside air of the building is of great importance for utilizing the potential (Høseggen 2008). This theory is integrated in the use of the values of effective heat capacity presented in table 1 in the calculation of the result outputs in this thesis.

TES can be used in different applications, but considering the topic of the thesis, only electric load management is analyzed. Vennemo et al. (2017b) implies that in some residential buildings, the temperature is lowered at night to save energy, successfully utilizing the principle. However, the authors stresses that the power requirement also will be greater the next morning since the temperature is raised in the morning to cover both ordinary losses and additional heating requirement due to lowered night level temperature. This approach works as the opposite of what a DR event is trying to achieve, raising the peaks in demand load curves and thus not achieving the need of flexibility in these peak periods. In a DR event, the principle of TES is used by shifting electrical loads in the form of sensible heat from peak periods to off-peak periods. During off-peak periods, electrical loads are generating heat which raises the temperature in all surrounding materials with a temperature raise higher than the normal temperature setting. Potentially on a cold January morning. As the time of the peak period and flexibility need arrives, electrical loads are disconnected completely. To this point, surrounding interior materials has been charged with sensible heat and act now as a TES. While the electrical loads stay disconnected, the materials will discharge the heat to surrounding indoor environments contributing to the duration of electrical loads can stay disconnected before thermal comfort is jeopardized. When the temperature is raised above the set-point, the thermal inertia principle sets in allowing the buildings to stay in an agreed thermal range comfort in a small timeframe. Generally, a maximum theoretical duration of three hours is normal but considering heat losses in the form of ventilation and transmission and considering personal consumer preferences etc., the realistic use of the TES principle potential will be maximum 1.5 or 2 hours with utilization from hour zero decreased with roughly 20-25% and 45-50% respectively (Kringstad et al. 2018). With this approach, using TES during a DR event, it enables to flatten and stabilize end-users load profile (Arteconi et al. 2012).

Figure 7 shows the relation between effective heat capacity and space heating demand met by electricity in a building stock. If a building possesses a high total effective heat capacity including that the electricity space heat demand is high, potentially large amounts of energy can be shifted. However, if the heat demand is low, the result output changes (Vennemo et al. 2017a).

		Effective heat capacity, (*Wh/m2*)	
		High	***Low***
Heat demand met by electricity (*W/m2*)	***High***	Large amounts of energy shifted: High load reductions, medium duration	Small amounts of energy shifted: High load reductions, short duration
	Low	Large amounts of energy shifted: Small load reductions, long duration	Small amounts of energy shifted: Small load reductions, medium duration

Figure 7: Load reduction, duration and energy shifted as a function of effective heat capacity and heat demand met by electricity. From Vennemo et al. (2017a).

2.4 Norwegian residential trends in energy use and space heating

2.4.1 Energy use

Total energy use in the Norwegian residential sector doubled from 1960 to 1995 while population and average consumption per household (up to approximately 1970) increased. The electricity share of total energy use increased from a share of 35% in 1960 to over 70% in mid-1980s (Bøeng 2005). Looking at total energy use in the entire residential segment from the period 1990-2017 subdivided onto source of supply regardless of type of activity, figure 8 clearly shows that electricity has been the dominant source throughout the whole period. Norway has an exceptional high share of electricity regarding energy consumption in the residential segment comparing other countries. There are large consumption of electricity, both in the residential segment and the other demand sectors in the country (Bøeng 2005; Magnussen et al. 2012). One factor is the incredible amount of hydropower access with high efficiency and low operating costs making electricity inexpensive (Sandberg 2017; Söder et al. 2018).

Therefore, incentives to invest in technologies like district heating has been rather sparsely compared to the other countries in the Nordic region (Bøeng 2005; Fazeli et al. 2016).

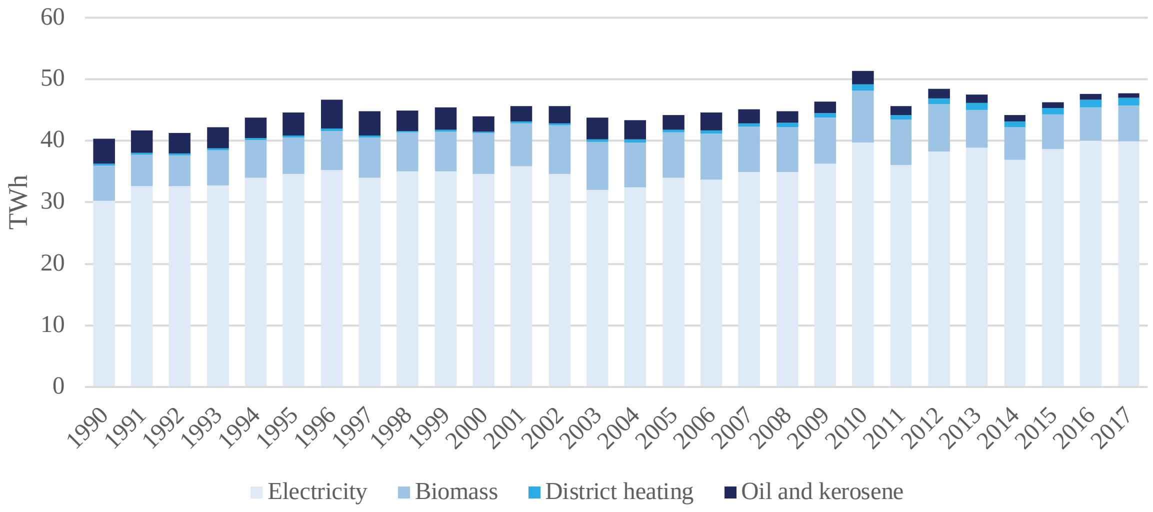


Figure 8: Energy use (in TWh) in the Norwegian residential building sector concerning all end-use activities. Data extracted from Statistics Norway.

Since 1990, electricity use has been increasing from roughly 30 to 40 TWh in 2017. Electricity share of total energy use has been increasing with a growing rate last years, from 1990-2012 with an average share of roughly 77% to an average 83% in 2013-2017 (figure 9).

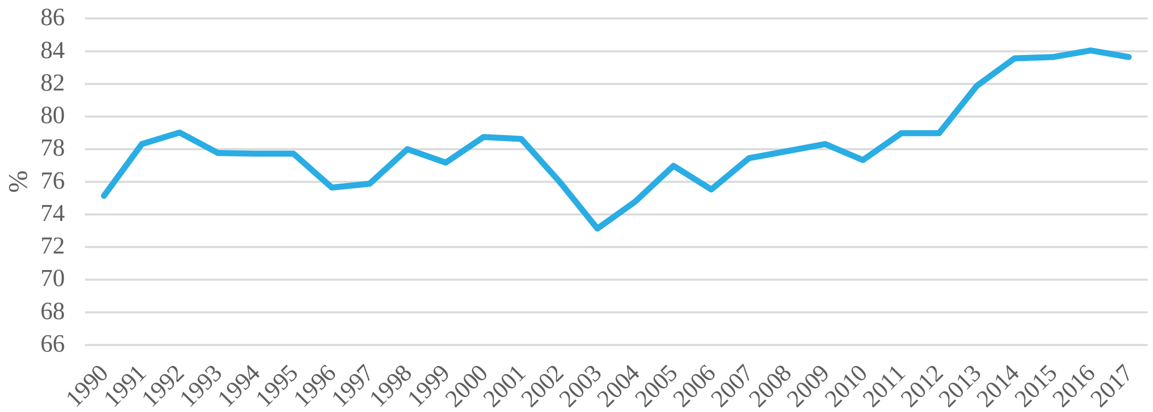


Figure 9: Percentage share of electricity use in the Norwegian residential building sector concerning all end-use activities. Data extracted from Statistics Norway.

Households switching and replacing oil heating systems to direct electric heating or air-to-air HPs has been seen as a factor for the late upturn (Lien & Spilde 2017) According to Kipping & Trømborg (2015), the use of air-to-air HPs in Norway has seen a significant increase the last decade, where in 2012, 27% of air-to-air HPs were installed in Norwegian residential households. Wood and wood pellets are the second most important source of energy. The use of biomass has been increasing modestly from 5.7 TWh in 1990 to 8.4 TWh in 2010 which was a particularly cold year (appendix 2) but declined in the period 2011-2017. In 2017, biomass accounted for 5.8 TWh of total energy use which is a 12 % share. District heating has a limited role regarding total energy use and is only apparent in the largest cities in Norway. Where district heating is established is mainly connected to multi family houses and non-residential buildings (Kipping & Trømborg 2015). However, the use of district heating has increased with a slow rate from 0.3 TWh in 1990 to 1.3 TWh in 2017. Fossil fuels as end-use sources in the segment has very minor roles today. After 2020, oil heating systems will phase-out completely (Kipping & Trømborg 2015) and it is expected that consumers that has used kerosene and oil for heating will change to electricity (Magnussen et al. 2012). In the period 1990–1999, fossil fuel consumption amounted to around 4 TWh per year but has diminished since 2000 and in 2017 it amounted to roughly 0.7 TWh. Altogether, energy consumption in the residential segment amounted to just under 50 TWh in 2017.

After 1990, growth in energy consumption has been limited and leveled out due to a combination of several factors. Hille et al. (2011) elaborates that a slower increase in per capita living area has been the most decisive factor, while reduced energy use per m^2 has been the second most contributing factor. A milder climate since 1980 has also been a benefactor which has led to a decrease in energy need for space heating purposes. How much energy of which energy products is used is affected by outside temperature. Electricity which is used in several appliances such as lighting, heating and in different equipment stands out from the rest of the energy products like oil, wood and district heating which is only used for heating. Use of the latter products is therefore affected more by outside temperature than electricity is (Bøeng 2005; Hille et al. 2011; Lien & Spilde 2017; Magnussen et al. 2012). Reduced growth in living space per person is another important factor. Magnussen et al. (2012) found that growth in living space per person decreased from 2.5% per year before 1990 to 1% per year after 1990. More efficient use of energy because of more energy-efficient electrical and non-electrical equipment and changes in knowledge, attitudes and preferences along with policy instruments has led to lower energy use per square meter living space. Hille et al. (2011) found that aggregating a selection of changes in energy end-use areas during the period 1990-2009 constituted a reduction of 41 kWh/m^2/year. Incremental energy saving measures, integration of HPs and a reduction in heat loss because of increased heating efficiency were among the actions that caused the reduction in the period (Hille et al. 2011).

Continued flat development of energy use by 2020 will be the trend (Lien & Spilde 2017). Towards 2035, it is expected that electricity usage in all buildings in Norway including residential households will largely stay the same. It is expected that electricity as el-specific end-use activity and direct heating will decrease and the use of HPs will increase, by the fact that it will replace both oil furnaces and some direct electric heating. When old residential buildings are replaced by new buildings, average energy efficiency in the residential building stock will increase which will make up for the expected increase in Norwegian population leveling out electricity use. If local production of solar PVs in the residential segment increases towards 2035, will the overall use of electricity decrease as an effect. Therefore, future electricity usage is difficult to predict (Spilde et al. 2018).

Households that are being renovated to new technical standards, e.g. TEK10 and TEK17 including nearly zero energy buildings (nZEB) and passive house standards improves the performance of the existing building stock with increased insulation performance and refurbishment measures of the envelope in residential buildings. Improvements of the building stock reduces overall heat loss from the building body (Magnussen et al. 2012). Table 2 shows the history of Norwegian technical building regulations through time in terms of maximum overall heat transfer coefficient, U (W/m^{2}K). Stricter U-values have emerged through time influencing the building performance of new constructions which have increased average energy efficiency of the total Norwegian building stock.

Table 2: Maximum overall heat transfer coefficient, U-value (W/m2K). Technical regulations in Norway through time. Outer wall, roof, ground floor and windows/doors in terms of U-value. Windows/doors per usable area in terms of maximum percentage regulation. From various references.

Regulations	Building components				
	Outer wall	Roof	Ground floor	Windows/ doors	% wind/door per BRA
Regulation 1949 (Bøhn & Ulriksen 2006)	≤0.93-1.16	≤0.93	-	-	-
Regulation 1969 (Bøhn & Ulriksen 2006)	≤0.58-1.28	≤0.46-0.58	≤0.46	-	-
Regulation 1985 (Bøhn & Ulriksen 2006)	≤0.45	≤0.23	≤0.23-0.30	≤2.10-2.70	-
Regulation 1987 (Bøhn & Ulriksen 2006)	≤0.30	≤0.20	≤0.20-0.30	≤2.40	-
Regulation 1997 (Bøhn & Ulriksen 2006)	≤0.22	≤0.15	≤0.15	≤1.60	-
TEK10 (Perera et al. 2014)	≤0.18	≤0.13	≤0.15	≤1.2	≤20%
TEK17 (DIBK 2017)	≤0.18	≤0.13	≤0.10	≤0.80	≤25%

However, Høseggen (2008) lists several reasons for an increase in energy use despite stricter requirements. Increased use of large glass facades in new buildings has increased energy use because the heat loss through glass are higher than insulated walls. Increased demand of quality indoor climate due to low energy prices has led to low focus on energy efficiency and increased use of lighting and equipment.

The mix of the building stock change concerning age, e.g. new and/or improved buildings and demolition of old buildings. There are large apparent variations in energy use in terms of kWh per square meter and how the energy is used for different types and age classes of buildings. Old, not renovated buildings use the most energy concerning age class. Detached houses use the most energy concerning type. Bøeng (2005) reported an average use of 25 MWh per year for a detached house, while block apartments use the least amount of energy with an average use of 10 MWh per year for a block apartment in the period before year 2005. Heating with oil, wood and pellets is more common in detached houses than in block apartments. In block apartments, panel heaters and district heating are more common. Bøeng (2005) points out that consumption increases with increased usable area and number of people in the dwelling. The author addresses that consumption in a block apartment is less than half of the consumption in a detached house, which is related to differences in average living space, and that block flats receives heat from heating activity from the surrounding apartments (Bøeng 2005). Urban migration which has increased the last years leads also to changes in the building stock, e.g. larger share of the population moves into apartment blocks where it requires less living space per person. This eventually lead to a decline in total usable area which inflicts total energy use (Hille et al. 2011). Besides urbanization, Magnussen et al. (2012) mention a sharp rise in house prices as a factor contributing to the changes in living space per person (Magnussen et al. 2012).

2.4.2 Space heating

Space heating can be covered by various energy products and different technologies, such as HPs, electric radiators, wood or pellet burning stoves or with oil furnaces. Electric appliances can only be powered by electricity and which is often called electricity-specific energy consumption which includes electricity for electrical appliances and lighting (Hille et al. 2011). The most important source of energy for heating is electricity, commonly combined with wood stoves and air-to-air HPs (Kipping & Trømborg 2016). In a study conducted by Magnussen et al. (2012), the authors found that electricity covers 70-80% of the heating requirement, while the remaining part is mainly covered by bioenergy (7%), oil (7%) and district heating (4%) (Magnussen et al. 2012). In Norway, many households have several alternative heating options.

In a survey study conducted by Bøeng et al. (2014), the results showed that almost all households (96%) had electrically based heating equipment in 2012. At the same time, 70% had heating equipment based on biofuel or oil, while 15% had waterborne systems. In homes built after 2008, 42% had a waterborne system. There are large variations among different types of housing. Over 90% of households in detached houses have the opportunity to fire with biofuel, oil or gas, and in block apartments only 28% have this possibility. On the other hand, many block flats (32%) have waterborne systems based on central heating, including district heating or HPs (Bøeng et al. 2014). The TABULA/EPISCOPE project discussed later in the thesis, has list the average electricity use percentage as energy ware for space heating quantified to three different segments, seven cohorts and three refurbishment states of the Norwegian residential building stock shown in appendix 4-6 (DH stands for the use of district heating).

In 2011, energy consumption for heating amounted to 66% of the energy consumption in the dwellings (Magnussen et al. 2012). Magnussen (2012) points out that several studies indicates that heating is higher in residential buildings than previously assumed. According to the authors, several reports have previously calculated a space heating demand of 58 %, but new studies indicate a 66 % share (Magnussen et al. 2012). Hille et al. (2011) have quantified the total Norwegian energy use in the residential sector in four main categories according to building type. For detached houses (single family houses) and semi-detached houses (terraced houses), the results showed that of total energy use, space heating accounted for 70% and 60% respectively, while in apartment blocks (multi family houses) the use of space heating just accounted for 23% (Hille et al. 2011). Looking at electricity use in the Norwegian residential segment; figure 10 shows that space heating has been the most important end-use activity between the period 1990 to 2017 increasing from 20 to roughly 25 TWh.

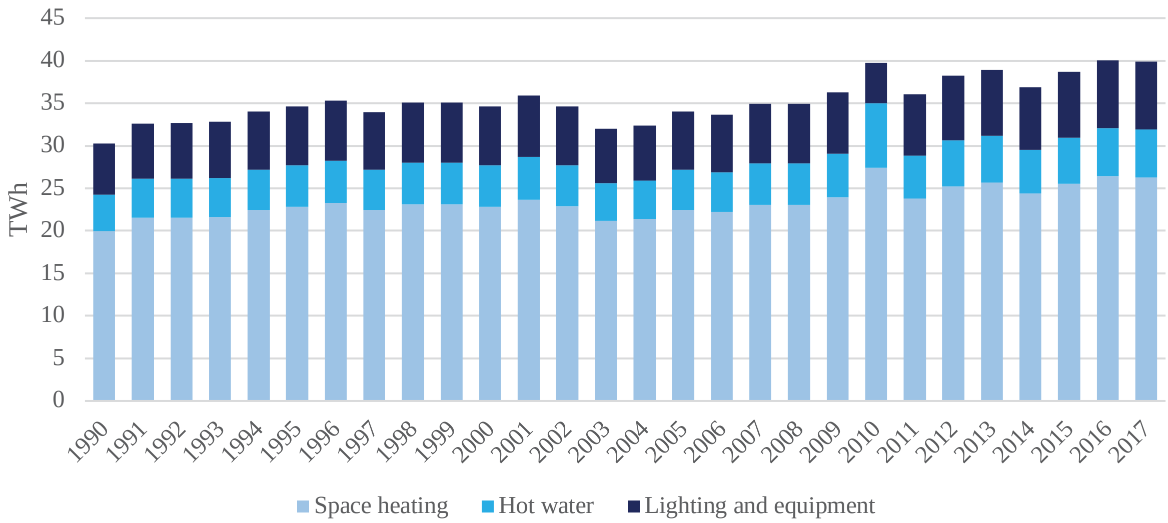


Figure 10: Electricity use (in TWh) in the Norwegian residential building sector divided by end-use activities. Data extracted from Statistics Norway. 66% of space heating, 14% hot water and 20% lighting and equipment (70% space heating used in 2010). Percentage share set by use of Magnussen et al. (2012).

Magnussen et al. (2012), Prognosesenteret (2012) and other reports have found significant potential for reducing energy consumption for heating in the residential segment. It is expected that the energy requirement for space heating will be further reduced in time (Magnussen et al. 2012; Prognosesenteret 2012).

2.4.3 Rebound and prebound effects

When applying an energy efficiency measure or just considering energy use in terms of space heating in buildings, Tennbakk et al. (2013) addresses that some actions do not deliver the expected measured energy use which is technically calculated beforehand. The measurement is underestimated. This effect occurs because of changes in user behavior of the energy use in buildings. This effect, known as a rebound effect causes minimization of a calculated energy saving or an increase of energy of the expected total when just considering the use of energy. Users of households, according to literature, has variable tendencies to consume more energy which is expected beforehand, for example due to a need of increased comfort or increased use of energy services which represents a benefit for the household. A prebound effect however, can take place if the calculation of expected energy use or energy savings in a building is overestimated, which means for example that energy consumption before an energy efficiency measure is lower than estimated. The effect can be a result when using average values when for example calculating technical energy use potential. Tennbakk et al. (2013) informs that, in principle, prebound can also lead to underestimation of potential of energy savings, if the energy consumption is underestimated before a measure. Tennbakk et al. (2013) stresses that it is relevant to decrease the degree of a prebound because the effect gives wrong estimations of the result. Tennbakk et al. (2013) argue that more detailed and realistic data estimates of energy use of building stocks can potentially remove an impact of the prebound effect. A literature review by Tennbakk et al. (2013) has been conducted about the profoundness of rebound effects in the Norwegian building sector. The review shows that we know little about the scope of the effects in general, but that many studies reports significant rebound effects in their studies (Tennbakk et al. 2013). Other takings from the review:

- The rebound effect is larger in terms of space heating than electrical heating equipment. The authors interpret it as because the cost of energy linked to electrical equipment constitutes a minor part of the cost of using appliances and it is more difficult to regulate energy consumption in electrical equipment.
- The rebound effect shows a decreased importance for wealthy households than for lesser wealthier households. The authors argue that this occurs because wealthy households probably have an energy consumption that is close to the desired optimal comfort level including that the entire living space is heated at all times. Less wealthier households can have an indoor temperature which is lower including that smaller parts of the living space are heated during the winter. If the cost of the space heating service in less wealthier households decreases, the authors find that this scenario can emerge in a period of larger energy use. A connection is also found between household income and a degree of environmental awareness.
- Operation of smart meters can reduce the rebound effect because the system is less aware of the relationship between electricity consumption and the costs. If the costs were to reduce it would not have as much impact on consumption than if operated manually.
- Consumers that have access to information appear to be more price sensitive which can inflict a greater rebound effect when the costs decrease because the consumption increases. Meanwhile, the authors argue that when users have information on own consumption, especially compared to those who do not, have an impact which reduces the rebound effect overall (Tennbakk et al. 2013).

3 Norwegian residential building stock development from 1960 to 2100

The parts in this chapter presents the overall development of the Norwegian residential building from the past in 1960, the present today and the future through 2100. 3.1 firstly introduces the concept of a building stock model and how this is implemented into the thesis. 3.2 and 3.3 continues to give descriptions of material that is used in this thesis to conduct the analysis of this thesis. Lastly in 3.3.2 is computed output of the building stock model used further in the analysis of the thesis outlaid.

3.1 Building stock model approach

A building stock is a compilation of all the buildings in one or multiple segments or it can be all buildings on a national level. According to Sandberg (2017), a building stock model have different approaches, whether it is accounting, quasi-stationary or a dynamic approach, where the latter further can be divided into stock-driven or input- or activity-driven. A building stock model can either include one or multiple types of buildings, it can bear one or multiple cohorts and the scope can either be for one or multiple years. Models with an approach of accounting consists of quantification of the stock in terms of size and composition including an energy or material analysis of the results, which exclude analyzing affecting drivers of stock development and energy use. Quasi-stationary approaches which normally has a scope of a single year and dynamic approaches which analyses changes over multiple years are modelling approaches which use the drivers that interact with a building stock and attempts to explain the size, composition including the energy consumption of the stock. Activity driven models under the dynamic approach normally use construction and demolition rates as drivers, while stock driven models relies on time-changing factors which can be about the population or the different lifestyles people live which can have a large effect in total. The composition of a national building stock consists of fairly different cohorts as in physical characteristics, whether it is different types of buildings, different building age classes, sizes or technical standards. Development of national building stocks attempts to say something about different segments of the building stock. Several models attempt to develop national building stock models for the purpose to analyze and evaluate different aspects in the stock as for example energy use or energy efficiency measures (Sandberg 2017).

A dynamic residential building stock model has been developed the last decade. The purpose has been to simulate long-term development of residential buildings. This building stock model has been developed further by the PhD candidate Nina Holck Sandberg at the Industrial Ecology program at NTNU. Sandberg has also been a part of the work prior to the Intelligent Energy Europe (IEE) project TABULA/EPISCOPE at NTNU. While the thesis and the project were ongoing they mutually made use of each other's work. The residential building stock model of Nina Holck Sandberg has been a key part of this thesis, within the use of both energy and thermal mass analysis of the Norwegian residential building stock. The IEE-project TABULA/EPISCOPE has also been a part of this thesis using pictures of different buildings in segments and cohorts, computed transmission and ventilation losses distributed to the segmented residential building stock including computed average electricity intensities extracted from the TABULA WebTool (IWU 2017). Descriptions of the IEE TABULA/EPISCOPE project and the building stock model of Sandberg (2017) follows in the next subchapters.

3.2 Description of IEE-project TABULA/EPISCOPE

The IEE-project TABULA (Typology Approach for Building Stock Energy Assessment) which was conducted in the time period 2009-2012, residential building typologies were developed for several European countries. Norway was not a participator in the TABULA project but was added in the improved follow-up IEE-project EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks) which was conducted between 2013-2016 (IWU 2016). Development of the national residential building typologies in the EPISCOPE project follows the classification principle developed in the TABULA project but is adapted to the evolvement in the individual country's building stock and building tradition through time. The follow-up project EPISCOPE is a project extending through 20 countries and is funded by the EU IEE program. Into the project, new buildings and Nearly Zero Energy Buildings (nZEB) has been implemented. The project manager in Norway has been professor Helge Brattebø (NTNU), with SINTEF Byggforsk as subcontractor under local management of senior researcher Igor Sartori. The focus of the combined projects has been to monitor the development in the respective national building stocks in terms of physical characteristics and potential measures for energy efficiency in the building stock including applying scenario analysis as a basis to provide input to ongoing policy processes and applied policy instruments concerning energy consumption use in buildings. The objective was to make the energy refurbishment processes in all European residential sectors transparent and effective, and the building typologies in the different countries are able to be compared against each other since they use the same applied method (Brattebø et al. 2014; Sandberg 2017). Typologies for all 20 participating countries is presented in an all-access web-based service named TABULA WebTool (IWU 2017).

3.3 Description of building stock model of Sandberg (2017)

The building stock model of Sandberg (2017) uses a dynamic modelling approach with a stock-driven element. Because of the long timespan of existing buildings, a stock driven approach allows a long modelling time-span which has a timeframe of 160 years (Sandberg et al. 2017). Figure 11 shows a conceptual visualization of the building stock model. Sandberg (2017) identifies the core of the stock-driven dwelling stock model as the yearly demand for dwellings, which is based on changes in population (P_t) and number of persons per dwelling ($P_{D,t}$). Annual construction (D_{new}), demolition (D_{dem}) and renovation (D_{ren}) activity has been calculated. Their corresponding rates are outputs from the model. Sandberg (2017) claims that traditional stock models often use linear or simplified assumptions on how construction, demolition and renovation activities in the building sector change over time. To achieve reliable and valid results she argues that a more detailed and non-linear dwelling stock model should be applied. Sandberg (2017) elaborates further that a lifetime probability function is applied concerning previous construction activity, to estimate annual quantity of demolition activity. Mass-balance principles are used to determine the quantity of construction activity. Sandberg (2017) elaborates that *"the model is not able to – and not meant to – describe short-term variations in the system, but instead the model successfully reproduces the historical long-term development and the actual stock composition"*.

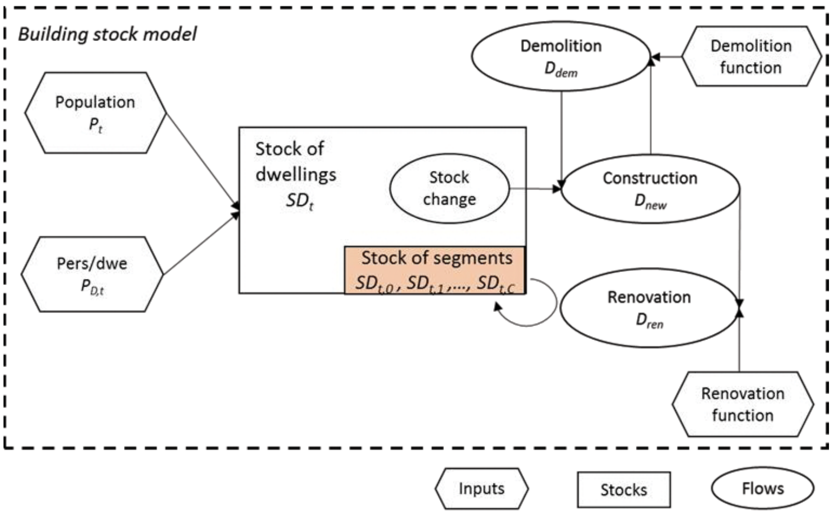


Figure 11: Representation of the building stock model of Sandberg (2017). From Sandberg (2017).

The building stock model constitutes different methodologies and approaches explained and used in following papers where Sandberg has been either first author or a part of the paper:

Paper 1: *Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock* (Sandberg et al. 2014b).

Paper 2: *Sensitivity analysis in long-term dynamic building stock modeling – Exploring the importance of uncertainty of input parameters in Norwegian segmented dwelling stock model* (Sandberg et al. 2014a).

Paper 3: *Dynamic Building Stock Modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU* (Sandberg et al. 2016a).

Paper 4: *Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960-2015* (Sandberg et al. 2016b).

Paper 5: *Dynamic Building Stock Modelling: General algorithm and exemplification for Norway* (Sartori et al. 2016).

Paper 6: *Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016-2050* (Sandberg et al. 2017).

In paper 5, the general algorithm for the building stock is described. Further information about the segmented building stock model can be found in Sandberg (2017).

3.3.1 Building stock typology

The Norwegian residential building stock of Sandberg (2017) is segmented into different residential building types and construction periods (cohorts). To find specific characteristics of the residential building stock, it is needed to quantify it into building typologies. For all building types and for all refurbishment states, the two building age classes in the model; -1800 and 1801-1955 has been grouped together naming the new building age class: -1955.

The resulting building typology output used in this thesis is presented as follows:

3 building types:

- SFH - Single Family Houses – detached houses and farmhouses
- TH - Terraced Houses - Semi-detached house, townhouses, chain houses and terraced houses
- MFH - Multi Family houses – Apartment blocks and buildings for communities

8 age classes:

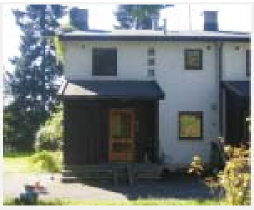
- Up to and including 1955
- 1956-1970
- 1971-1980
- 1981-1990
- 1991-2000
- 2001-2010
- 2011-2020
- 2021 and beyond

3 refurbishment states:

- A1 - Original state (not rehabilitated)
- A2 - Standard rehabilitation
- A3 - Future rehabilitation

Archetype 1 is floor area/households in their original state (not rehabilitated) or rehabilitated to the same standard as the original state before 1980. Archetype 2 is floor area/households that is rehabilitated in the period 1980-2020. In Sandberg (2017), an assumption is made that these households have undergone the same "standard rehabilitation" as defined in TABULA/EPISCOPE. Archetype 3 is floor area/households that is rehabilitated in the future (Sandberg 2019). Table 3 shows a visualization of an average representation of a typical house/block in the Norwegian building stock quantified by type and construction age class. The pictures used in the visualization is taken from the web-based service provided through the TABULA/EPISCOPE project (IWU 2017). It shows a representable quantity of the building stock used in this thesis.

Table 3: Representation and visualization of average buildings quantified to segments and cohorts in the Norwegian residential building stock. Pictures extracted from IWU (2017).

Year class	SFH	TH	MFH
-1955			
1956-1970			
1971-1980			
1981-1990			
1991-2000			
2001-2010			
2010-2020			
2021-	No picture	No picture	No picture

3.3.2 *Building stock model result output*

The Norwegian residential building stock model is presented in figure 12, 13 and 14 with a building type distributed to each figure. In each figure, construction age classes are presented as total floor area in millions in the time period 1960-2100. Finally, the total Norwegian building stock is presented in figure 15 representing refurbishment states as total floor area in the same period. Largest cohorts in all segments are -1955 and 2021-. -1955 is large because -1800 and 1801-1955 are combined. 2021- is large because future construction age classes are not integrated into the model which would decrease the quantity of 2021-.

SFH (figure 12) is the largest segment in the Norwegian residential building stock over the whole period. From 1960 to around 2003, the segment constitutes 70% of the total building stock. The percentage decreases to around 40% in 2100. From 1960 to 1990, including all construction age classes, the SFH segment increases with 60 million m^2 total floor area. From 1990 to around 2020, the increase in the segment stalls. From 2020 through 2100, the segment levels out completely and decreases slightly. Besides the two mentioned cohorts -1955 and 2021-, 1981-1990 is the largest cohort through the whole period.

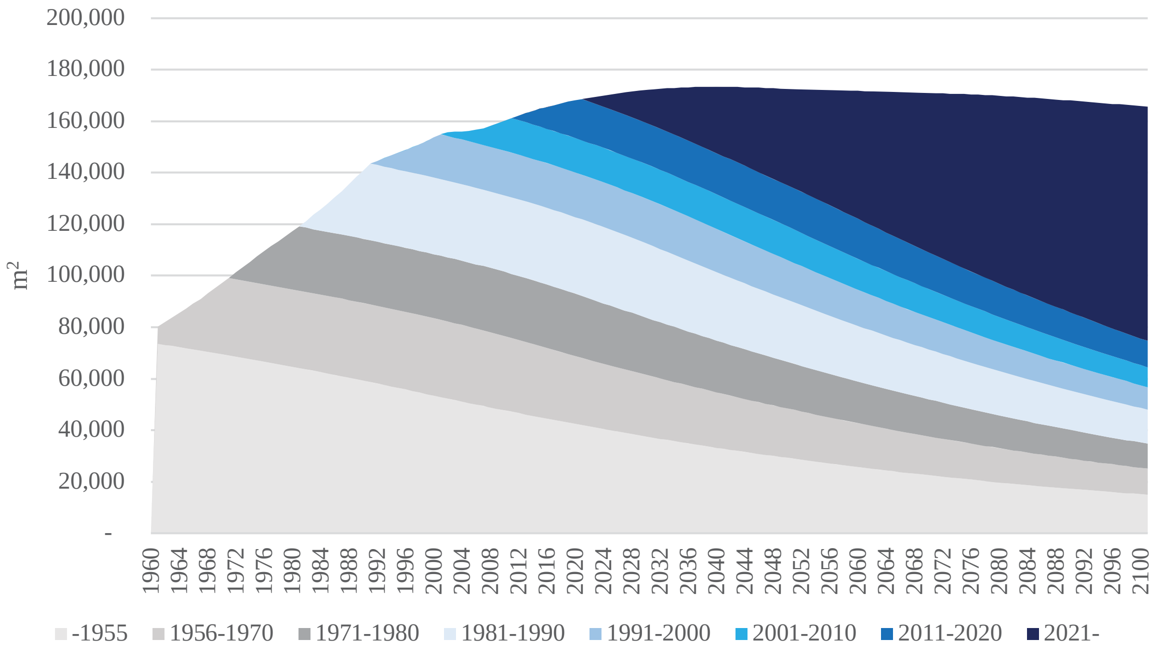


Figure 12: SFH segment of the Norwegian residential building stock in total floor area in million m^2 quantified in cohorts. From Sandberg (2017).

TH (figure 13) is the second largest segment in the building stock from 1960 to 2030 but becomes the smallest segment from 2030 through 2100. The segment constitutes around 20% of the total building stock throughout the whole period. From 1960 to around 2010, including all construction age classes, the TH segment increases with 22 million m^2 total floor area. The increase rate increases from 2010 to 2025 but obtains the same increase rate after 2025. Around 2073, the segment stalls through 2100. 2011-2020 is the largest cohort through the whole period besides -1955 and 2021-.

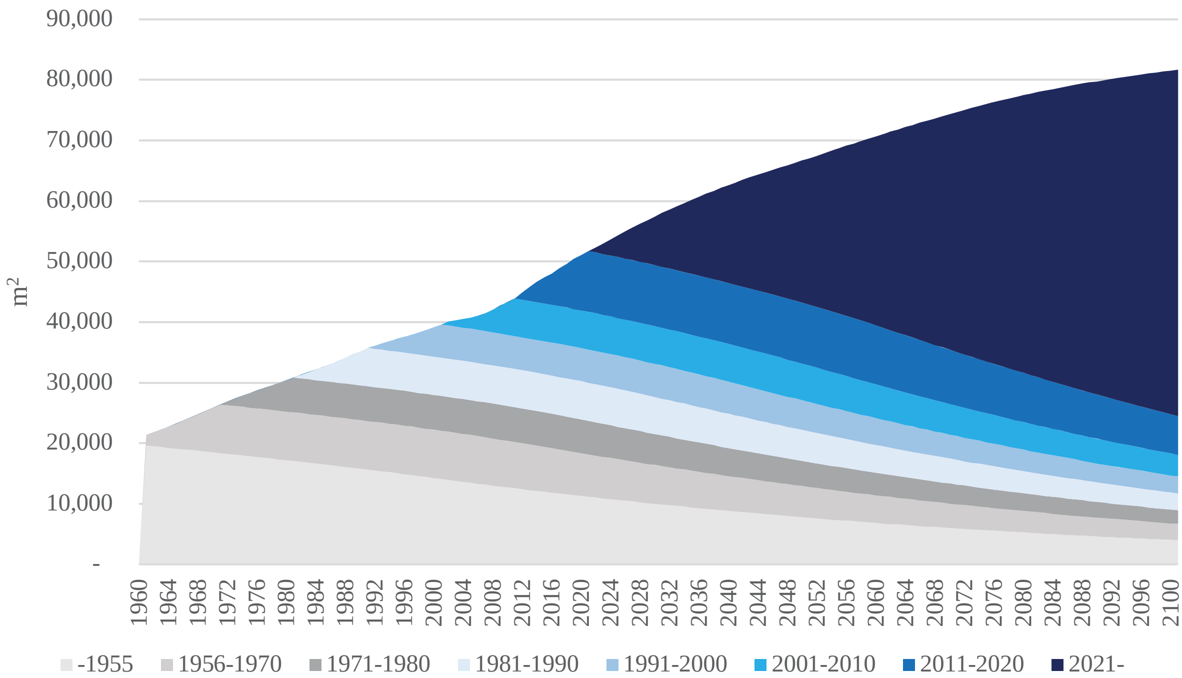


Figure 13: TH segment of the Norwegian residential building stock in total floor area in million m^2 quantified in cohorts. From Sandberg (2017).

MFH (figure 14) is the smallest segment from 1960 to 2030 but becomes the second largest from 2030 through 2100. From 1960 to 2000, the segment constitutes 10% of the total building stock. The percentage increases to almost 40% in 2100. From 1960 to 2001, including all construction age classes, the MFH segment increases with a minor increase rate. From 2001 through 2100 however, the increase rate change significantly as the segment increases with over 120 million m^2 total floor area. 2011-2020 is the largest cohort through the whole period besides -1955 and 2021-, however it can be assumed that one of the future construction classes will be the largest cohort in the segment due to the large increase from 2001.

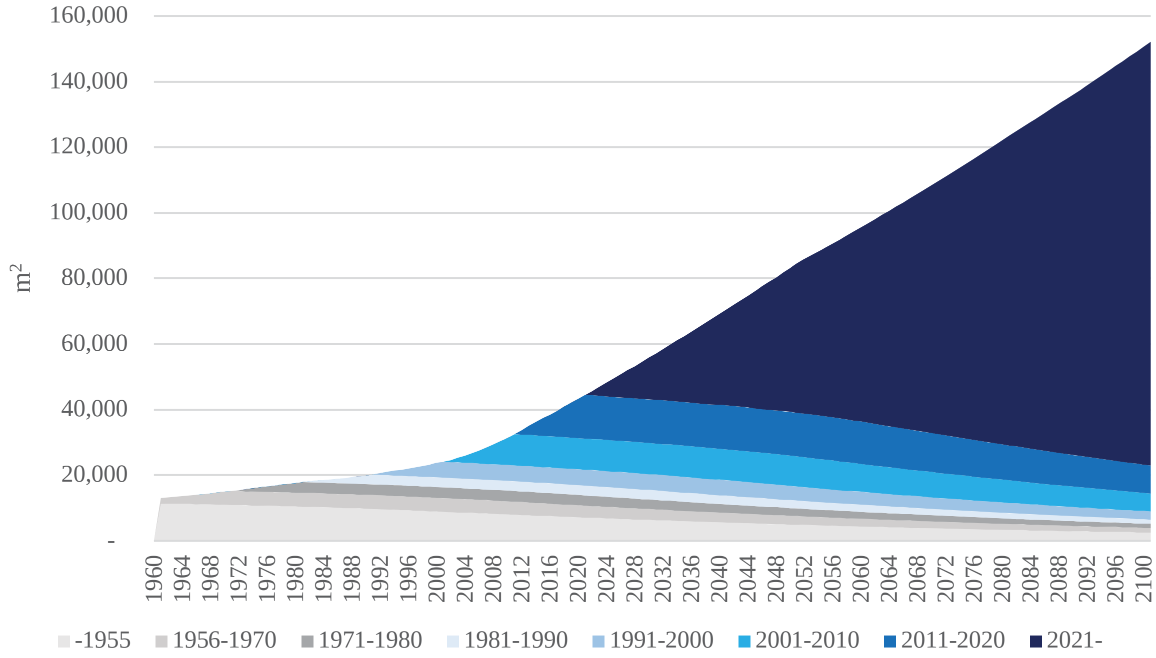


Figure 14: MFH segment of the Norwegian residential building stock in total floor area in million m^2 quantified in cohorts. From Sandberg (2017).

Figure 15 shows the total Norwegian residential building stock in terms of different refurbishment states. The building stock increases in the whole period from a little over 100 million m^2 total floor area to roughly 400 million m^2. Original states in respective segments of the building stock constitutes the largest share of the total refurbishment states and has large shares even through 2100. Standard rehabilitation is refurbishment of the building stock in the period 1980-2020. Future rehabilitation is registered from 2033 in the figure.

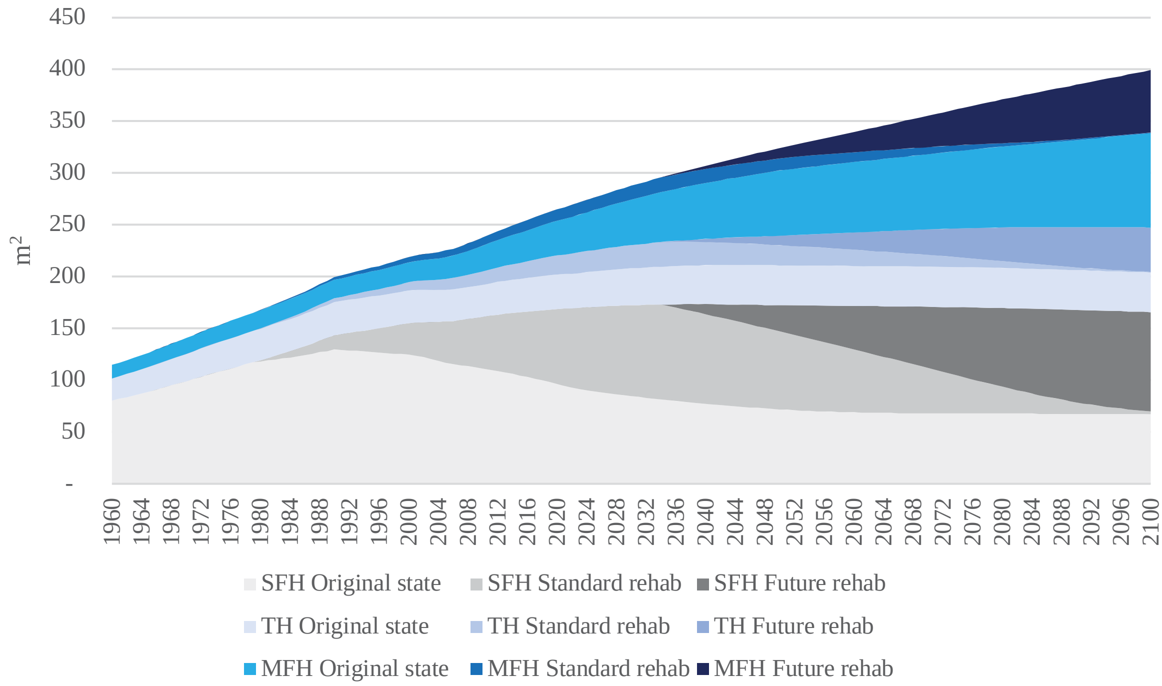


Figure 15: The Norwegian residential building stock in total floor area in million m^2 quantified in refurbishment states and segments. From Sandberg (2017).

4 Projection of electricity use as space heating in the Norwegian residential building stock

The parts in this chapter presents the analysis conducted in this thesis in terms of projected electricity use as space heating in the Norwegian residential building stock in between the period from 1960 to 2100. 4.1 introduces the concept of a building stock energy model and how this is implemented into the thesis including simplifications and assumptions taken to compute the result outputs. 4.2 presents the results of the analysis of projection of electricity use as space heating in this thesis. The results are assembled through different variations of nuances in the context of space heating use with electrical equipment in the building stock. Lastly, load shifting potential in a DR event in Norway is presented for the period 1960 to 2100.

4.1 Description of building stock energy model of Sandberg (2017)

Building stock energy models commonly use either a “top-down” or “bottom-up” approach, where “top down” is described as a study with an energy analysis and macro-economic variables. “Bottom-up” models, however is more appropriate for technological analysis of the building stock. Typically using historical data of thermal and physical properties of individual houses or segments of the stock which evolves into an analysis of the energy use in specific houses. The model can thereafter up-scale to exhibit the whole building stock fairly accurate (Reynders 2015; Ürge-Vorsatz et al. 2012). As explained earlier, the Norwegian residential building stock of Sandberg (2017) is segmented into a set of chosen building types and construction age classes. Sandberg (2017) argue that such a segmentation is useful for energy analyses as dwellings within each segment have similar characteristics and energy demand, while comparing different segments a large variation can exist in terms of different characteristics and energy demand. A segmented model is therefore offering a more precise resolution argue Sandberg (2017) further. In the PhD thesis of Sandberg (2017), she has developed the building stock further for application to aggregated energy analyses of the building stock which has a time period from 1960-2050. This developed energy model is used further in this thesis to determine delivered electricity to space heating with adjacent electricity analyses. The segments in the building stock are distributed to so called archetypes in terms of refurbishment states, thus allowing for changes in energy intensity after renovation. Combining the development of the building stock model with archetype- specific energy intensities, total energy demand is calculated. Sandberg (2017) estimates the energy intensities *i(t)* of a building by the use of the standard *Calculation and energy performance of buildings – Method and data*

(Standards 2019). To determine the energy demand of a single dwelling in year *t*, *e(t)*, the average energy intensity in the dwelling *i(t)* is multiplied by the size of the dwelling *a(t)*:

$$e(t) = a(t) * i(t)$$

Energy efficiency changes in the building stock for example in terms of the building envelope leads to adjusted energy demand. To determine the energy demand of the total building stock in year *t*, *E(t)*, the average energy intensity in the stock *I(t)* is multiplied by total heated floor area in the stock *A(t)*:

$$E(t) = A(t) * I(t)$$

In building stocks, total heated floor area adjusts over time, as the stock develops in size and composition. The average energy intensity adjusts over time by changes in energy efficiency of the building stock in terms of construction, demolition and renovation including heating systems. Sandberg (2017) points out that both *A(t)* and *I(t)* change over time. Evolution of adjusted energy demand is based on detailed analyses, while the changes in total heated floor area demands complex modelling. Energy intensities and total energy demand can be measured as energy need or delivered energy. Energy need is the quantity of energy needed for space heating and cooling, DHW including ventilation and electrical appliances and depends upon the technical standard of the building envelope. Delivered energy however is extracted from energy need and is the quantity of energy which is delivered to a dwelling to fulfil the demand of energy, accounting for onsite energy generation and losses in the heating system (Sandberg 2017). Figure 16 shows the concept of the building stock model with the extension of the building stock energy model. Extensions from the building stock conclude distribution of segments to archetypes including a stock floor area (*SA*) layer and energy layers (*EN* and *DE*). Delivered energy accounts for HP, $HP_{t,c}$, and PV, $PV_{t,c}$, contribution, share of energy carriers, $C_{t,c,e}$, including weighted average efficiency, $\eta_{t,c}$, extracted from the layer *EN*. Changes of energy efficiency by renovation is implemented by the use of these archetypes. The building types and cohorts from the building stock is quantified onto these archetypes. As the building stock, the energy model uses three renovation periods which determine if and when a dwelling was last renovated. Paper 4 describes model and input data in terms of the energy model for period 1960-2015 and paper 6 for the period 2016-2050. In the period 1960-2015 of the building stock, a calibration of the energy model against statistics is conducted.

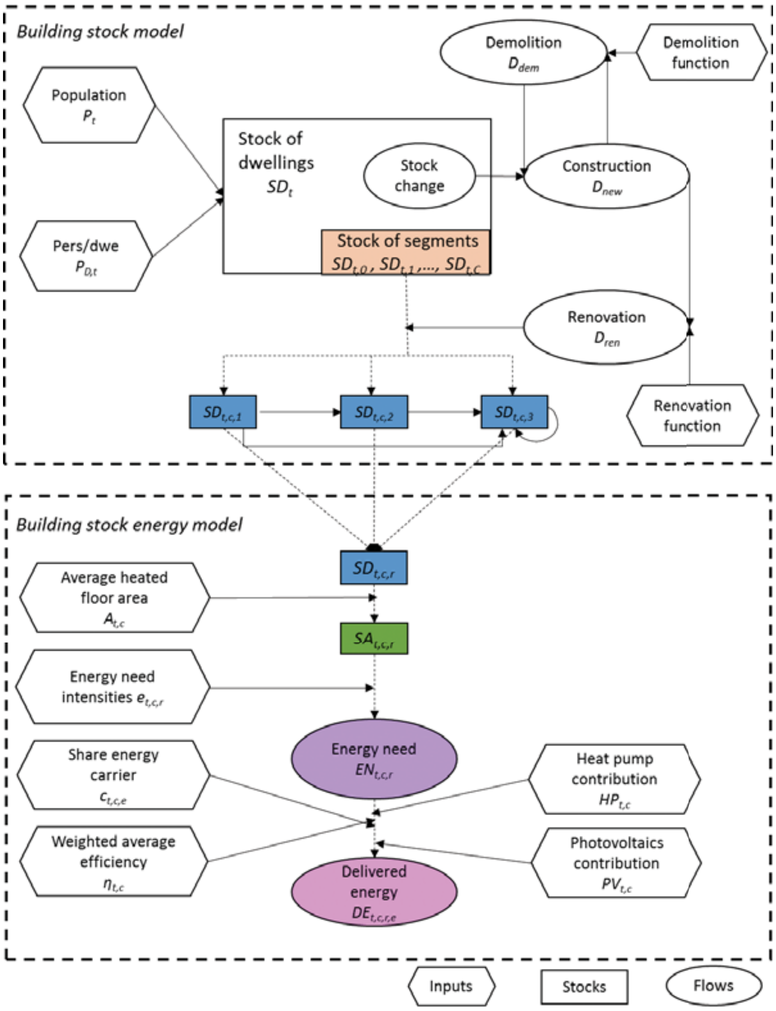


Figure 16: Representation of combined building stock model and building stock energy model of Sandberg (2017). From Sandberg (2017).

The same archetypes in the building stock model, discussed earlier, is used in the energy model. Energy need intensities used in the energy model are described in the Norwegian residential building typology from the EPISCOPE project (Brattebø et al. 2016). Figure 17 shows the values used for all building types for eight cohorts and the three archetypes for space heating and DHW.

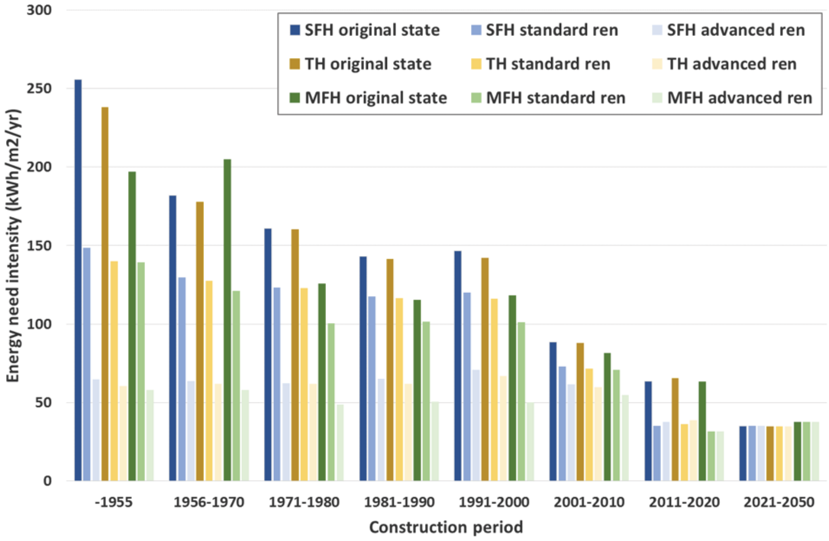


Figure 17: Energy need intensities (in kWh/m²/year) of segments, cohorts and refurbishment states. From Sandberg (2017).

The energy model uses thermal adaptation factors to correct for factors that make real observed energy demand differ from theoretical estimates. Correcting for user behavior and prebound/rebound effects introduced earlier, including model uncertainties are applied in these factors. Figure 18 shows the combined thermal adaptation factor which is the function of average delivered energy intensity for heating. Estimation of the factor involves using all available empirical Norwegian data, energy use statistics, case studies and the Norwegian EPC database. The "jump" in year 2015 (figure 18) is due to different methods applied to the historical and future energy analysis. The period from 1960-2015 and 2016-2050 must therefore be analyzed separately (Sandberg 2019). Output from the energy model show that average theoretically estimated energy need intensity per m² of heated floor area in the Norwegian residential building stock (figure 19) decreases from 241 kWh/m² in 1960 to 139 kWh/m² in 2015 in terms of combined space heating and DHW by energy efficiency measures through renovation and construction of new, improved buildings. In 2050, the energy need intensity for space heating and DHW will be 88 kWh/m². Technical estimated delivered energy is based on calculations of technical qualities of the building. Estimated "real" delivered energy intensity, corrected for the thermal adaptation factor, decreases from 183

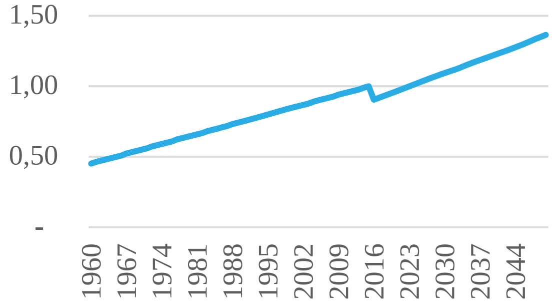


Figure 18: Thermal adaptation factor. Extracted from the energy model in Sandberg (2017).

kWh/m^2 in 1960 to 127 kWh/m^2 in 2015. The intensity will further drop to an average value of 74 kWh/m^2 in 2050.

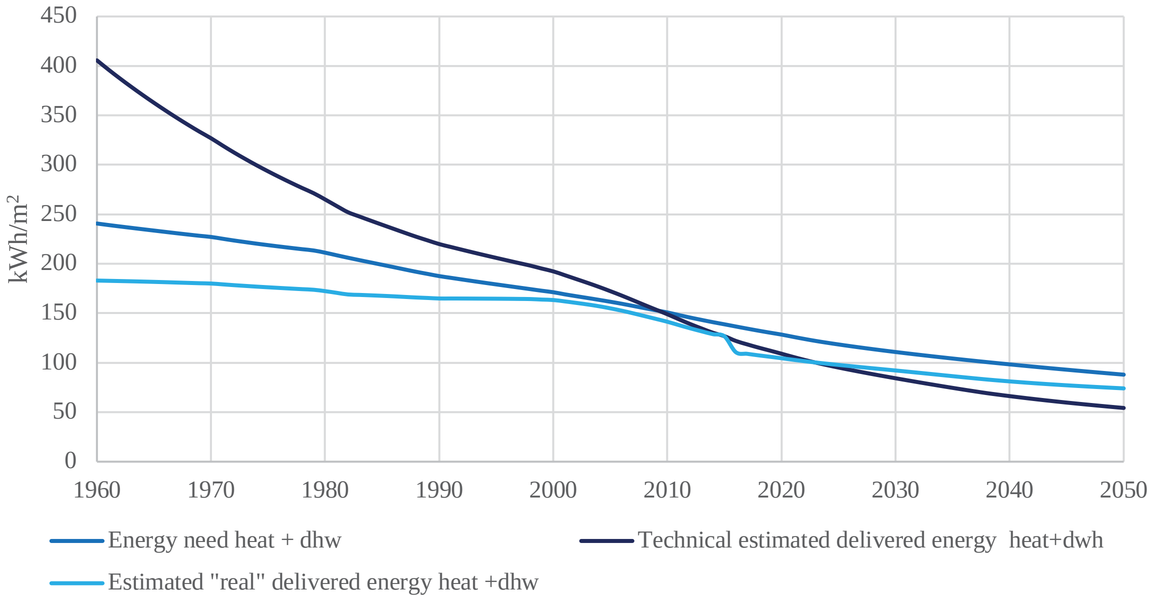


Figure 19: Heating and DHW (in kWh/m^2) in terms of energy need, technical estimated delivered energy and estimated real delivered energy. From Sandberg (2017).

Estimated "real" delivered energy in terms of space heating and DHW per m^2 and per person will have the same pattern from 2000 throughout 2050 (figure 20). Weighted average heating system efficiency for all segments in the building increases from 64% in 1960 to roughly between 87-96% in 2015. The increase is due to historical shifts to more efficient energy carriers and heating systems. Energy efficiency potential has been realized with standard renovation. Further information about the energy model can be found in Sandberg (2017) including the different papers presented earlier.

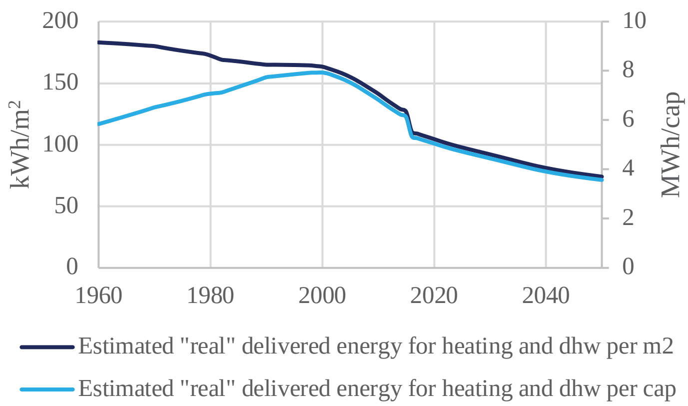


Figure 20: Estimated real delivered energy for heating and DHW per m2 (in kWh) and per person (in MWh). From Sandberg (2017).

In the energy model, scenario analyses are applied to study evolution paths in terms of different assumptions. Sandberg (2017) calculates five scenarios of "real" estimated delivered electricity in Norway in the period 1960-2050. The annotation of "real" estimated is correction for climate and indoor temperature including the use of the adaptation factor (Sandberg 2019). The five scenarios simulated is as follows:

- Baseline
- Frequent renovation
- Minimized energy need
- Extensive HP & PV
- Minimized delivered energy

For all five scenarios modelled, Sandberg (2017) estimates total “real” estimated delivered energy combining all energy carriers and technologies which is electricity, biofuels, oil, DH and PV and HP contribution and for different end-use activities which is heating, electricity to appliances and DHW. The baseline scenario extracted from the work of the PhD thesis of Sandberg (2017) is used to calculate, “real” estimated delivered electricity as space heating in the period 2050-2100. Further information about scenario baseline can be found in Sandberg (2017). Figure 21 shows result output from the energy model in terms of total estimated “real” delivered energy for the Norwegian residential building stock with use of various energy carriers. Electricity is and will be the most important energy carrier in terms of heating and DHW. Especially after heating with oil is phased out. Total demand for heating and DHW will decrease from 28 TWh per year in 2015 to 24 TWh per year in 2050. However, including electricity to appliances, total estimated “real” delivered energy considering all end-use activities shows that the trend is almost constant with 38-39 TWh from 2015 to 2050, with the increase of electricity to appliances making up for the decrease in use to heating and DHW. The “jump” in 2015 is due to the thermal adaptation factor. Further reduction potential in terms of advanced and/or more frequent renovation is rather limited according to Sandberg (2017). But by use of local energy HP and PV the potential can rise significantly in terms of delivered energy. Combining factors for maximized utilization of HP and PV in the system, can reduce the demand by roughly 2 TWh in 2015 or 10 TWh in 2050. The results in a scenario analysis for future development of the building stock in period 2016-2050 establish the prediction other reports are predicting, that future savings in energy demand will emerge. User behavior will also be important in the future according to Sandberg (2017).

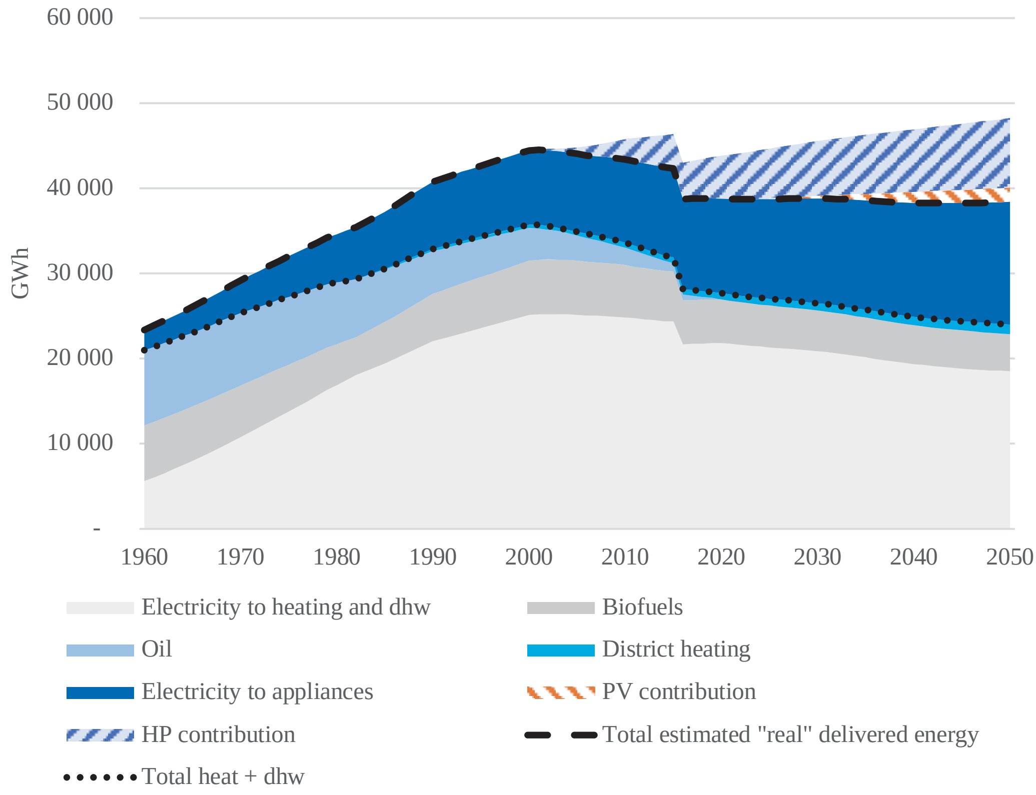


Figure 21: Estimated "real" delivered energy (in GWh). Total demand and use of various energy carriers. From Sandberg (2017).

4.2 Building stock energy model results

Building stock energy model results presented in this subchapter is conducted by use of data from the energy model of Sandberg (2017), but with own calculations declaring method conduct for each result output. A quantitative, accounting model approach is conducted by the use of the energy model of Sandberg (2017) with multiple segments, cohorts and archetypes. Bear in mind that there is some uncertainty attached to such an approach considering the result outputs, in fact analyzing energy or electricity future demand is difficult. Especially after 20-30 years, which makes an analysis through 2100 very difficult or almost impossible to predict, because of massive changes which predict future use of energy. Political influence being one of some large influencing factors for future use. Simplifications and assumptions taken in this thesis makes it even more uncertain. However, the results can give some assertiveness of the future of space heating and thermal mass in the Norwegian residential building sector.

4.2.1 Estimated "real" delivered electricity as space heating, all scenarios and baseline

4.2.1.1 Method, all scenarios 1960-2050

To find the estimated "real" quantity of delivered electricity as space heating for all scenarios Sandberg (2017) has projected, following procedure has been used:

1. In the energy model, electricity is calculated to heating and DHW combined for the total building stock. To find the amount of electricity used to space heating only, the two end-use activities must be split. By extracting the total single amount of space heating and DHW shares excluding DH regardless of energy carrier from the energy model and divide it by the total combined amount of space heating and DHW, a percentage of electricity to heating only has been extracted and multiplied by the amount of electricity to heating and DHW combined for the total building stock in the period 1960-2050.
2. For all scenarios in the energy model, number one has been applied.

4.2.1.2 Result output, all scenarios 1960-2050

Figure 22 shows all scenarios as estimated "real" delivered electricity as space heating. Apart from the baseline scenario, all scenarios show the same trend from 1960 up until around 2015. In that period, all scenarios including baseline show a strong increase, over quadruple the amount of delivered electricity. Around 2002, all scenarios experience the highest point in the period, accounting for around 23.7 TWh delivered electricity for all scenarios excluding baseline and baseline accounting for around 22.5 TWh delivered electricity. From the period around 2002, the trend however shifts to a decreasing trend. Because of different calculation methods for future and historic energy use discussed earlier, the "jump" in energy use occurs in 2015, which do not correctly estimate "real" delivered electricity in around that period. The declining trend splits all scenarios into different pathways in around 2019. From this year through 2050, baseline shows the highest amount of delivered electricity, showing a fairly slow declining trend from 17.8 TWh in 2019 to 11.4 TWh in 2050. Frequent renovation follows almost the exact same pathway as baseline. The scenario minimized energy need shows a steeper slow declining trend, from 17.8 TWh in 2019 to 8.8 TWh in 2050. The scenarios extensive HP & PV and minimized delivered energy however shows the steepest large declining trend, for both scenarios 17.8 TWh in 2019 to just under 1.5 TWh for extensive HP & PV and 0 TWh for minimized delivered energy in 2050.

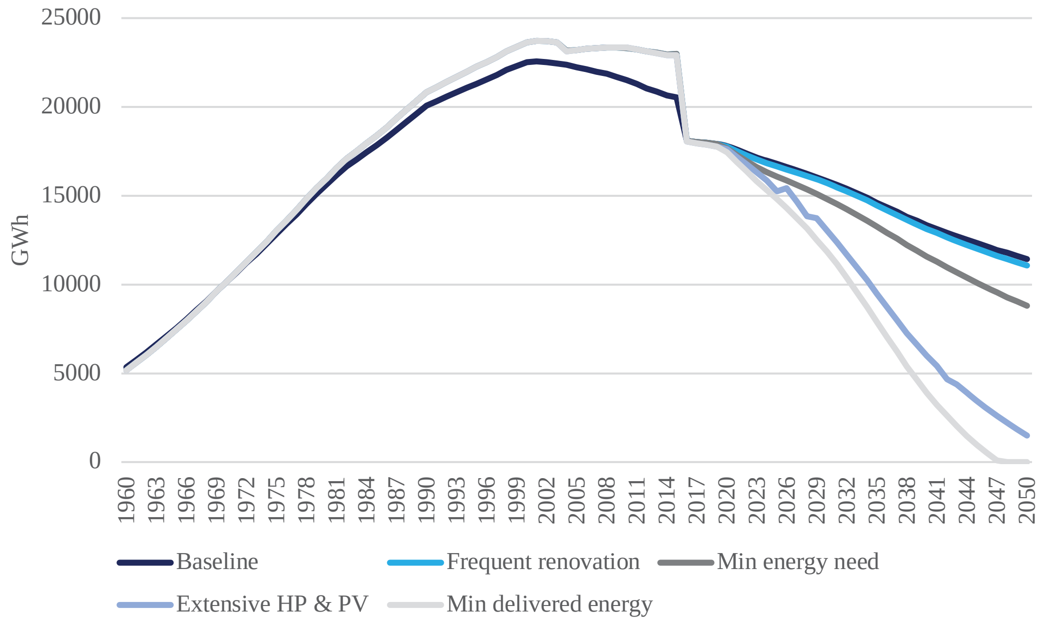


Figure 22: Estimated "real" delivered electricity (in GWh) as space heating. All five scenarios. From Sandberg (2017) with own calculations.

In this thesis, baseline has been intuitively picked as the representable scenario for delivered electricity as space heating in further calculations of electricity use to space heating. All other scenarios are therefore not discussed further in this thesis.

4.2.1.3 Method, baseline 1960-2100

To find the "real" quantity of delivered electricity as space heating for scenario baseline, quantified in the three building types SFH, TH and MFH with an extension of the estimation to 2100, following procedure has been used:

1. Procedure number one in 4.2.1.1 has been used to apply electricity to heating only for scenario baseline.
2. To find the amount of electricity used to space heating in the three building types respectively, the shares of the respective types must be split. Since the energy model, only calculates electricity usage to space heating and DHW combined for the three building types, these numbers are used to decide the share between the different building types. By extracting the total single amount of electricity use to space heating and DHW in the respective building types and individually divide the numbers by the total combined electricity usage of space heating and DHW for the stock, percentage shares for the building types in terms of electricity to heating and DHW has been extracted and multiplied by the amount of electricity use to heating

only for scenario baseline to show the quantification between the respective types in the period 1960-2050.

3. To extend the period of the percentage shares of building types to 2100, a simple rate of change method is applied. The negative rate of change, (1- (($x_{new} - x_{old}$) / x_{old})), between 2049-2050 for SFH and TH is found to be 0.0025972 and 0.0078393 respectively. These rates are applied in a mathematical function, (x – (x * rate of change), in the years between 2051-2100 for SFH and TH. To find the share of MFH, the function (1 - (SFH + TH)), has been used. While this method is simple and not accounting for different factors in the future, it shows the fairly same trend from 2019 to 2050.
4. The percentage output from the three building types has been individually multiplied by the total delivered electricity to space heating.
5. To extend the period of the total delivered electricity to space heating, the same simple rate of change method in number 3 is applied as a negative rate of change which is found to be 0.01524 between 2049-2050 for the total demand. This rate is applied in the same mathematical function in number 3 between the years 2051-2100 for the total demand.

4.2.1.4 Result output, baseline 1960-2100

Figure 23 shows that SFH is the most important type of building in terms of electricity usage for space heating in the whole period, while TH is the second-most important user type from the period of 1960 to around 2040, while MFH takes over as the second most important user type thereafter. SFH shows a very large increase rate from 1960 to 2002. The electricity use increases by over a threefold in that period, while for TH also triples the increase in that same period. MFH shows a slow increase in that same period. After 2002, SFH spikes and thereafter decreases with roughly the same rate of change before 2002, however as a negative. From 2002 to 2050, SFH demand decreases from 16.4 to 6.7 TWh, while TH demand decreases from 4 to 2.6 TWh. MFH is the only segment that increases in that period from 2.2 to 2.6 TWh respectively. From 2050 to 2100, the simple negative rate of change method, show that SFH demand decreases from 6.7 to 2.7 TWh. In that same period, TH and MFH demand decreases from 2.1 to 0.7 TWh and 2.6 to 1.9 TWh respectively.

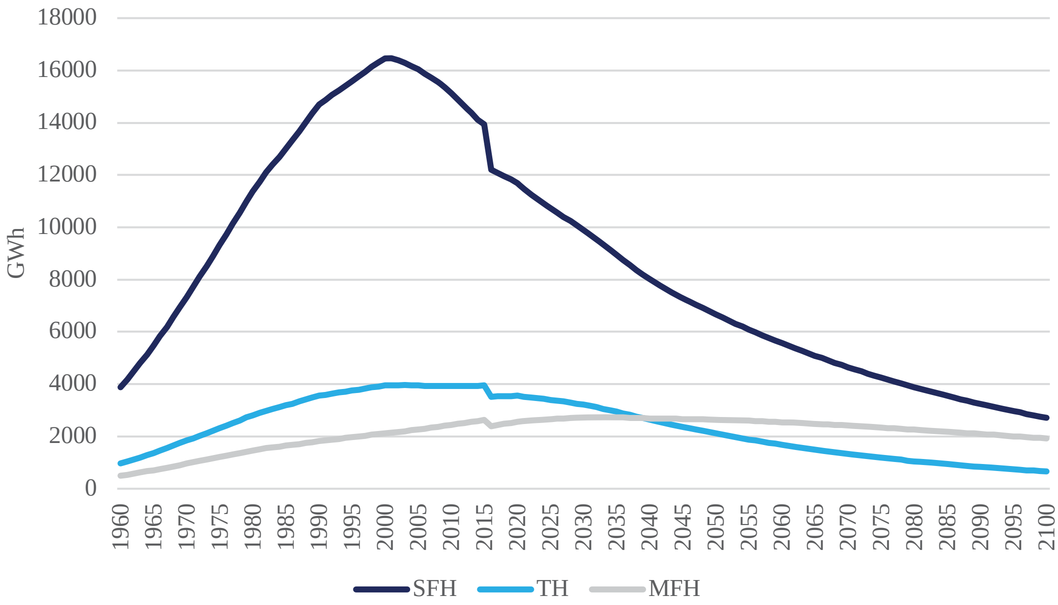


Figure 23: Estimated "real" delivered electricity use (in GWh) as space heating. Baseline scenario. From Sandberg (2017) with own calculations.

Figure 24 shows percentage share of the respective building types in terms of delivered electricity as space heating in the period 1960 to 2100 for the baseline scenario. The figure shows that SFH is the absolute dominant user type in terms of electricity for space heating accounting for over 70% of the total demand from 1960 to 2010, while the trend is declining from 2002, SFH continue to be the most important user type throughout the whole period. From 2040, the change of the second most user type occurs, while MFH in that period endure a strong increase of the total share, while TH show a slow decrease. In 2100, SFH stands for 51.2% of the total share, while MFH and TH stands for roughly 36.3% and 12.5% respectively.

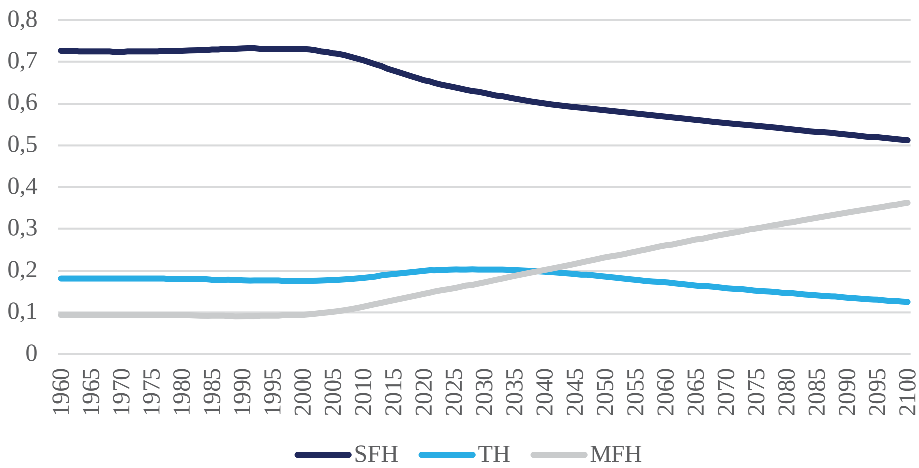


Figure 24: Percentage share of estimated "real" delivered electricity per segments. Baseline scenario. From Sandberg (2017) with own calculations.

4.2.2 *Estimated delivered electricity as space heating, average electricity intensities 1960-2100*

Estimated delivered electricity as space heating with use of data from TABULA/EPISCOPE is applied in this thesis to show the comparing between the result output from this method and the result output from the method applied in 4.2.1.3.

4.2.2.1 *Method*

Figure 25 (left) has been calculated by use of computed average electricity intensities extracted from the Tabula WebTool (IWU 2017). The average electricity intensities of space heating are multiplied with the segmented building stock model of Sandberg (2017) in terms of total floor area quantified to three segments. The average electricity intensities represent delivered electricity to space heating for each segment and for all cohorts in the Norwegian residential building stock. The process of computation of average electricity intensity is addressed in Loga & Diefenbach (2013). The computation is based on calculation of residential buildings extended with supply system balance of the buildings including roughly 60 referenced tables with constant and variable input data. It is accounted for construction element types by construction year classes including U-values, ventilation and transmission heat losses, the thermal envelope area of respective segments and cohorts and internal and solar heat gains as some factors involved. It is also applied an adaptation method. The computation of energy need for space heating is based on the standard EN ISO13790 with accordance to a one-zone model. Implementation of this method to Norwegian buildings is accommodated in an empirical fashion with different energy related properties according to Norwegian engineering practice (Loga & Diefenbach 2013).

4.2.2.2 *Result output*

Figure 25 (left) shows the resulting output of delivered electricity in the Norwegian residential building sector in the period 1960-2100 quantified onto the three building types analyzed in this thesis, by use of the building stock of Sandberg (2017) multiplied by the computed average electricity intensities in the TABULA/EPISCOPE project for each segment and cohort. For cohort 2021- in all segments, the same number is used as in cohort 2011-2020 to apply in the building stock of Sandberg (2017), due to the fact that the TABULA/EPISCOPE project compute only to 2011-2020. Comparing the two result output in figure 25 show the fairly same pattern for SFH in the building stock. Computed result output with TABULA/EPISCOPE data on the left (abbreviated to TE) and baseline on the right (abbreviated to B). TH (B) shows a much larger decrease from around 2016 to 2100 comparing TH (TE). Latter computed TH remains the second most important segment through 2100, while in TH (B) it does not. MFH (B) show a minor decrease around 2050, while MFH (TE) show a much larger decrease and from an earlier point in time, 2012. The SFH peak (TE) arrives in 1990 but is kept almost constant through 2001, the same year as the SFH peak (B) arrive. TE shows considerable larger amount of delivered electricity in SFH through the whole period, where the peak in TE is amounting to 20.6 GWh in 1990 and the peak in B is amounting to 16.5 GWh in 2001. SFH (TE), TH (TE) and MFH (TE) decreases to 6 GWh, 2.9 GWh and 0.5 GWh respectively in 2100, while SFH (B), TH (B) and MFH (B) decreases to 2.7 GWh, 0.7 GWh and 1.9 GWh respectively in 2100.

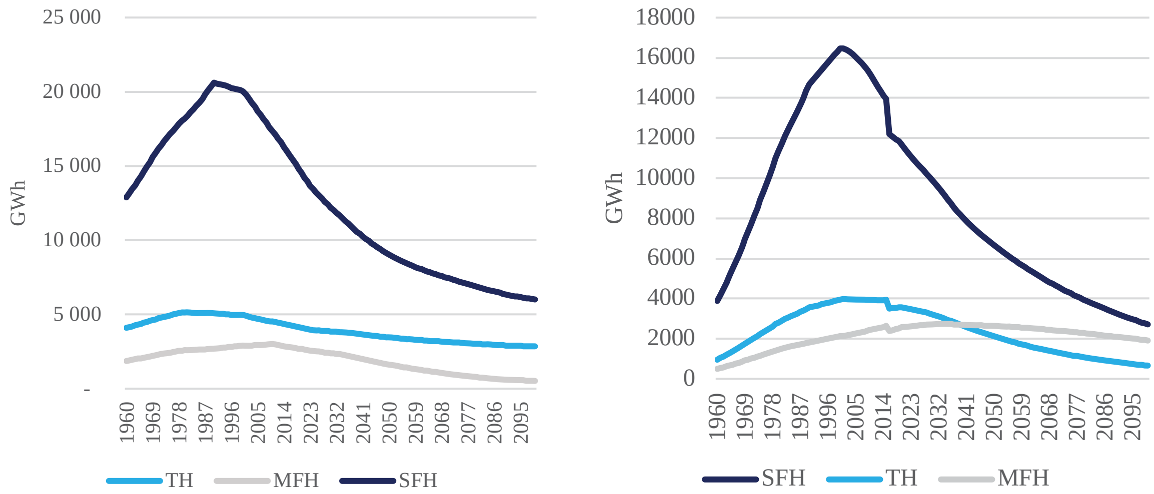


Figure 25: Estimated "real delivered electricity (in GWh) in the Norwegian residential building sector per segment with use of average electricity intensities from IWU (2017) (left) and baseline scenario (right). From Sandberg (2017) (right) and IWU (2017) (left) with own calculations.

4.2.3 *Estimated "real" delivered electricity as space heating per segment, cohort and refurbishment state, baseline 1960-2050*

Figure 26 is estimation of "real" delivered electricity as space heating quantified to each segment, two cohorts (-1955-2020 and 2021-) and refurbishment states (A1, A2 and A3) for the period 1960-2050.

4.2.3.1 *Method*

The output is calculated by using result output in 4.2.1.4 to quantify output for the different segments, cohorts and refurbishment states for the period 1960-2050 excluding the period after 2050.

4.2.3.2 *Result output*

Most noticeably is SFH A1 (-1955-2020) the most important share of all in terms of delivered electricity as space heating increasing from roughly 3.8 TWh in 1960 to 13.1 TWh in 2000. The share decreases largely however from 2000 to 2050. SFH A2 (-1955-2020) is the second most important share which registering a share in 1980 because of the standard renovation. The share increases to roughly 4.6 TWh in 2015 and decreases thereafter. The rest of the shares in the energy model is calculated to under 4 TWh in the whole period.

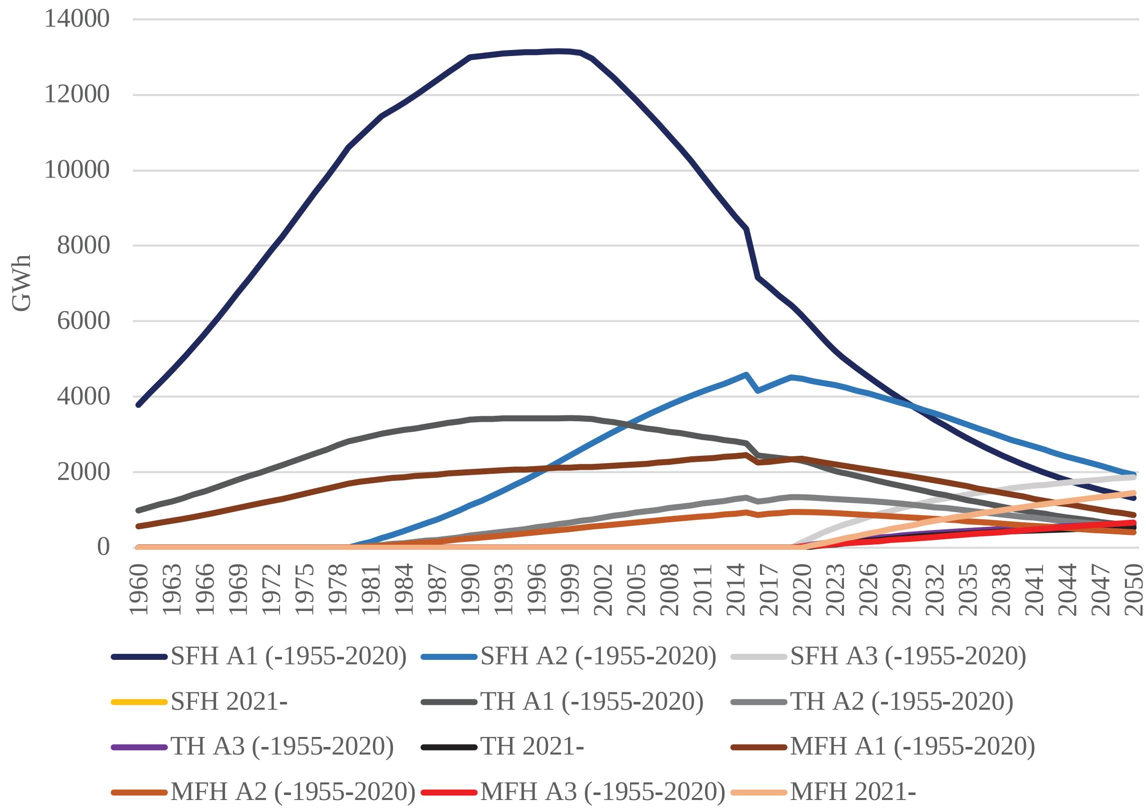


Figure 26: Estimated "real" delivered electricity (in GWh) as space heating per segment, cohort and refurbishment state. Baseline scenario. From Sandberg (2017) with own calculations.

4.2.4 *Estimated "real" delivered electricity as space heating per day, baseline 1960-2100*

4.2.4.1 *Method*

Total delivered electricity for space heating for an average day in chosen months is calculated by taking heating degree days (HDD) computed by Hansen (2018) from the period 2010-2018 and take the average from the average of all Norwegian county's HDD per year for all months in that time period and use it in the calculation (Hansen 2018). All values of HDD for an average value for each month in the time period is further quantified by a percentage given for all months. A time period of eight years will reflect the distribution in respective months. The percentages will give a somewhat average representation of how the energy use is quantified in an average month over a year. These percentages have been extracted and implemented in the dataset of total delivered electricity period 1960-2100 for all three building types visualized in figure 27, 28 and 29. Detailed description of the method is presented under:

1. Prior to the work of Hansen (2018), an excel sheet of calculated HDDs for all counties in Norway for period 2010-2018 is downloaded. Average HDD for each month in Norway used in this thesis is presented in Appendix 3 (Hansen 2018).
2. The average HDD value of all counties combined in each month in a year is extracted for each year between 2010-2018.
3. The average value of all years combined quantified to all 12 months in a year is calculated and extracted including average value for total HDDs over a year for all years.
4. Average value for each month is divided by total average value for a year to find a percentage share for each month in a year of delivered electricity as space heating
5. Percentage share for each month in a year is multiplied by the result output of 3.3.3 quantified to all building types in the period 1960-2100.
6. Result output from procedure five is divided by number of days in each month respectively for all building types in the period 1960-2100 to find daily demand in each month. Results are shown in GWh.

4.2.4.2 Result output

Figure 27 shows the result for an average day in chosen months in the segment SFH. January which is the month with highest overall electricity demand for space heating shows a large increase from 1960 to 2001, increasing the demand for an average day in January by over a threefold. Delivered electricity as space heating in an average day in January in 2001 amounts to 81.1 GWh, 58.3 GWh in 2019 and 11.9 GWh in 2100.

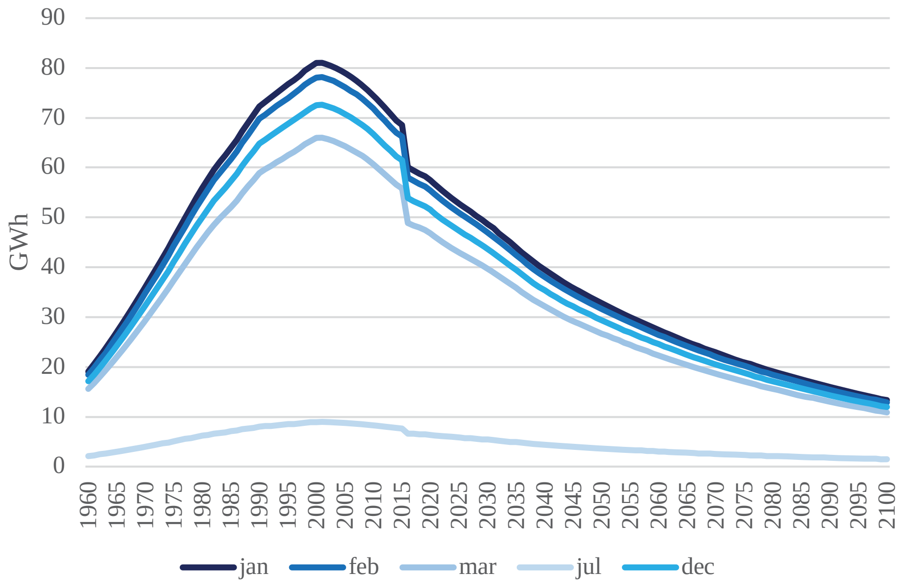


Figure 27: SFH estimated "real" delivered electricity (in GWh) as space heating per average day for chosen months. Baseline scenario. From Sandberg (2017) with own calculations.

By 2001 the peak is reached and turns to a decreasing trend. February, December and March respectively show the same pattern only with lower values. Comparing an average day in a January month to a July day it clearly shows that a January day have much larger total demand. However, the gap between the winter months is decreasing through 2100. Figure 28 shows the result for TH. TH shows the fairly same pattern as SFH except that TH has lower electricity demand than SFH in general. TH shows a strong increase from 1960 to 1990, while after the latter year the trend slows down and reach the highest demand year in 2003.

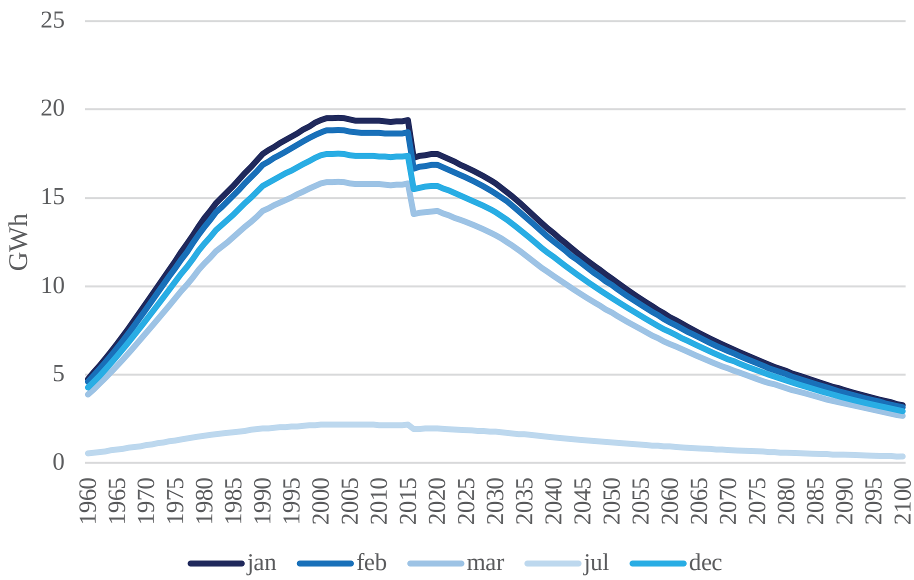


Figure 28: TH estimated "real" delivered electricity (in GWh) as space heating per average day for chosen months. Baseline scenario. From Sandberg (2017) with own calculations.

After latter year the trend flattens out until around 2015, where the differentiation in methods used shows. After 2015, TH shows a slow declining trend until 2100. The peak in an average January day in 2002 amounts to 19.5 GWh and decreases to 2.9 GWh in 2100. Figure 29 shows the result for MFH. MFH shows a different pattern than SFH and TH. While MFH also shows a strong increase from 1960 the increase continues through 2015 and continues further until the highest demand year in 2033.

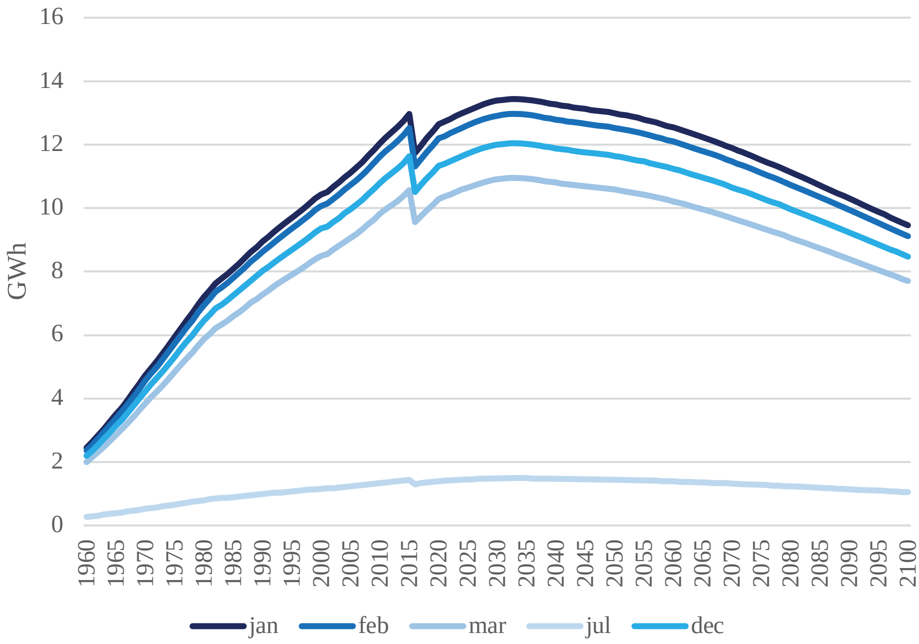


Figure 29: MFH estimated "real" delivered electricity (in GWh) as space heating per average day for chosen months. Baseline scenario. From Sandberg (2017) with own calculations.

After the latter year, the trend shows a slow declining trend until 2100. The peak in an average January day in 2033 amounts to 13 GWh and decreases to 9.1 GWh in 2100. It is also worth noticing that the gap between the winter months in MFH is larger and maintain the gap compared to SFH and TH where the gap is decreasing through 2100.

4.2.5 DR load shifting potential in segments and total building stock

Load shifting potential to use in a future potential scheduled DR event in Norway is estimated for the segments in the Norwegian residential building stock in a January month and for the total stock combined quantified to some chosen months in terms of GW. Scenario baseline is used to compute the result output for the two approaches. The potential is estimated for the period 1960-2100. Bear in mind that the calculation is uncertain, especially after 2050 since the estimation use a simplified calculation after this point. However, the results can give some assertiveness to what potential there lies in the Norwegian residential demand sector.

4.2.5.1 *Method, segments*

Method used to find load shifting potential for the month of January for the period 1960-2100 is described in detail as follows:

1. Result output from procedure six in applied method in 4.2.4.1 is used to further compute the load shifting potential.
2. The computed result output quantified to each month in all three segments analyzed in this thesis is divided by 24 hours to find the potential in power.
3. Result output from January in the period 1960-2100 for all three segments is presented in a summed figure of figure 30.

4.2.5.2 *Result output, segments*

Result output (figure 30) of calculated load shifting in terms of a potential scheduled DR event in a January month shows that SFH clearly inhibits the largest potential throughout the whole period from 1960 to 2100. While TH inhibits larger potential than MFH in around the peak in 2001, roughly around 2050 MFH overtake TH as the second most important source of load shifting potential through 2100. From 1960, the DR load shifting potential of the total Norwegian residential building stock increases from roughly around 1.1 to 4.6 GW in 2001. Thereafter the potential shifts to a decreasing trend to 3 GW in 2035, 2 GW in 2060. The potential decreases to the same level that is recorded for 1960, 1.1 GW in 2100.

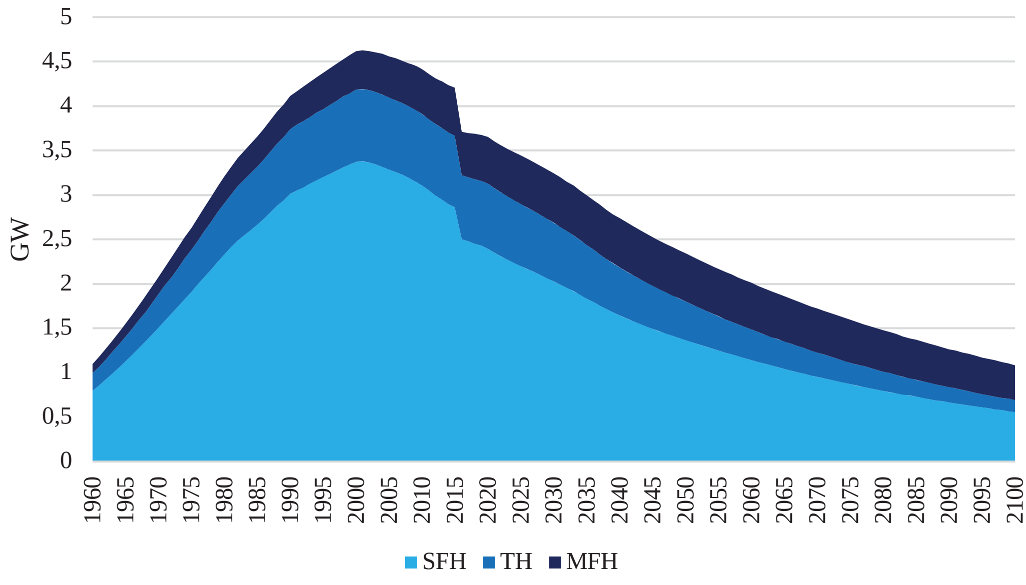


Figure 30: Estimated "real" load shifting potential (in GW) in January. Summed potential by segments. Baseline scenario. From Sandberg (2017) with own calculations.

4.2.5.3 Method, total building stock

Method used to find the load shift potential for the total building stock in terms of chosen months for the period 1960-2100 is described in detail as follows:

1. Result output from procedure six in applied method in 4.2.4.1 is used to further compute the load shifting potential.
2. The computed result output quantified to each month in all three segments analyzed in this thesis is divided by 24 hours to find the potential in power.
3. Result output from January, February, March, December and July is summed for the three segments analyzed as total residential building stock potential in the period 1960-2100 presented in figure 31.

4.2.5.4 Result output, total building stock

Result output (figure 31) of calculated load shifting in terms of a potential scheduled DR event for chosen months shows that January inhibits the largest potential throughout the whole period from 1960 to 2100. The gap between the chosen months however is decreasing through 2100. February, December and March in that order is the most important months after January. July shows a very low potential throughout the whole period.

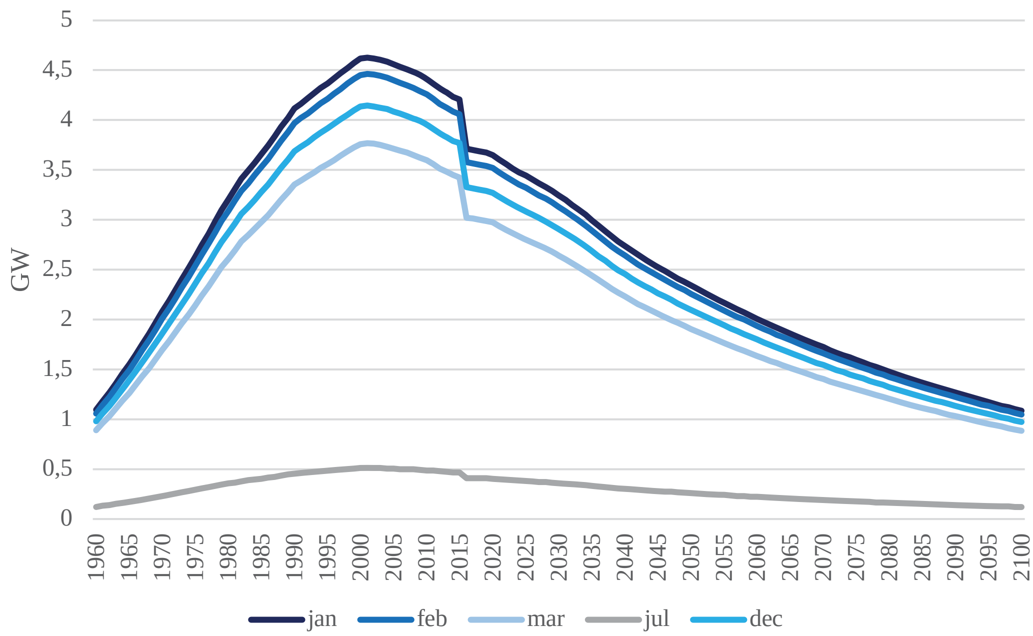


Figure 31: Estimated "real" load shifting potential (in GW) for chosen months. Average potential by total building stock. Baseline scenario. From Sandberg (2017) with own calculations.

5 Projection of thermal mass in the Norwegian residential building stock

The parts in this chapter presents the analysis conducted in this thesis in terms of projected thermal energy storage in the Norwegian residential building stock in between the period from 1960 to 2100. 5.1 introduces the method applied to conduct the analysis. Material and data are presented which has been a part of the conduct. Assumptions and simplifications taken concerning the projections are outlaid. 5.2 presents the results of the analysis of projection of thermal energy storage in this thesis.

5.1 Method

Thermal mass calculations of the total Norwegian building stock in the period 1960-2100 is deduced by use of effective thermal capacity as a single-deciding parameter. Effective thermal capacity is calculated in a bottom-up accounting model with a theoretical assumptive-intuitive rule-of-thumb approach quantifying interior partitions with a variation of different materials, which possess dissimilar thermal attributes including adjacent ratios of window to wall, internal wall and wall to floor. The model accounts only for the maximum potential available thermal capacity. In appendix 4-6, average transmission and ventilation losses as heat transfer coefficients is displayed for the total Norwegian residential building stock in terms of segments, cohorts and archetypes. Heat losses is important factors that has to be accounted for if “real” potential of load shifting is to be revealed, especially in terms of duration of a DR load shifting event. Calculation of thermal behavior in all segments, cohorts and archetypes is close to impossible to compute for as large as a sample that the Norwegian residential building stock is. Therefore, simplifications have to be made to compute the result output. The calculation does not account for unheated spaces, day and night zones, solar gains with orientation of facades which effect heat input from the sun. An assumption is made about uniform air temperature in all buildings.

To determine total area of interior partitions quantified to all cohorts in all segments in the Norwegian building stock, surface areas of partitions are calculated with the same assumptive-intuitive approach. The method applied bear an element of uncertainty, which can result in large variations of errors. Because specific information about interior material use in different segments of the Norwegian building stock including descriptions for different building age classes simply do not exist, sample outputs are difficult to match the “real world” output. Thermal capacities and thermal behavior dependent on large variational conditions in the different segments and cohorts in the stock is very difficult to compute without engineering models which can to some degree apprehend the large complexness of thermal behavior in different buildings. Dynamic building energy simulations, grey box modeling or the simpler reduced-order models are modelling examples that compute thermal behavior in buildings. Modelica which is a detailed building energy simulator is used by Reynders et al. (2014a) to quantify the Belgian residential building stock potential of thermal mass. In Reynders et al. (2014a), detailed simulations of building segments are conducted by the use of the IDEAS library developed at KU Leuven, which its outputs are implemented in Modelica which expresses detailed transient thermal processes. Engineering models like this computing the total thermal behavior of different buildings are more complex, but more difficult to use when applying it to a large sample size as for example residential building stocks. A simplistic accounting model is used in this case, which can be a foundation of further work.

The interior surface areas in all buildings used in the calculation of thermal mass is combined in the accounting model as interior and internal walls, floors, ceilings and windows. Difference between interior and internal walls, is that the latter represents walls that divide rooms inside a building, while interior walls represents the boundary walls adjacent to outside walls enveloping the building. Only the interior layers adjacent to buildings' inside air is used to calculate the thermal capacity. Thermal mass of windows is negligible. Due to this reason, windows are therefore not seen as carriers of thermal mass. Surface areas of floors quantified to different segments and cohorts in the building stock in Sandberg (2017) are used as the core of the thermal mass calculation of the stock. The quantification of area of ceilings in the stock is set equal to area of floor area, which assume that total square meters of ceilings is equal to total square meters of floors in the stock. However, some uncertainty of errors is attached using this assumptive method, which exclude buildings with unequal area of square meter comparing ceilings and floors. Surface areas of interior and internal walls are combined in the calculation of total area of walls quantified to different segments and cohorts in the stock, which relates to the compactness of a building. By compactness, the term explains how much surface area the effect of internal walls has to the combined wall area. To calculate the surface area of combined interior and internal walls, the report of Prognosesenteret (2012) is used to derive a wall-floor ratio to implement in the quantification of total surface floor area of the building stock of Sandberg (2017), due to the fact that such ratios is not existent in Norwegian building stock literature. To find average combined interior and internal walls for typical Norwegian dwellings a set of average dimensions of typical Norwegian dwellings derived by Prognosesenteret (2012) is used, represented in table 4 under. For simplicity, height, length and width is derived as interior walls. Since Prognosesenteret (2012) operates with seven cohorts, the cohort for 2011-, named 2011-2020 in this thesis, is copied to also represent 2021- (Prognosesenteret 2012):

Table 4: Average physical properties of segments and cohorts in the Norwegian residential building stock. From Prognosesenteret (2012).

Segment	Cohort	Height (m)	Length (m)	Width (m)	No. of units (#)	No. of floors (#)
SFH	-1955	2.6	8.24	8.86	1	2
	1956-1970	2.5	8.35	8.76	1	2
	1971-1980	2.4	7.01	10.8	1	2
	1981-1990	2.4	8.7	13.85	1	1.5
	1991-2000	2.4	8.52	12.48	1	1.5
	2001-2010	2.4	8.52	13.11	1	1.5
	2011-2020	2.4	8.52	13.11	1	1.5
	2021-	2.4	8.52	13.11	1	1.5
TH	-1955	2.6	8.12	13.32	2	2
	1956-1970	2.4	5.43	21.73	2	2
	1971-1980	2.4	5.38	21.51	2	2
	1981-1990	2.4	5.32	21.27	2	2
	1991-2000	2.4	6.65	15.11	2	2
	2001-2010	2.4	5.8	17.85	2	2
	2011-2020	2.4	5.8	17.85	2	2
	2021-	2.4	5.8	17.85	2	2
MFH	-1955	2.8	8.87	15.97	8	4
	1956-1970	2.7	7.7	34.18	16	4
	1971-1980	2.5	11.24	39.79	24	4
	1981-1990	2.5	11.45	40.07	24	4
	1991-2000	2.4	11.98	34.43	24	4
	2001-2010	2.4	11.16	37.93	24	4
	2011-2020	2.4	11.16	37.93	24	4
	2021-	2.4	11.16	37.93	24	4

An internal wall ratio is derived with an assumptive rule-of-thumb approach by using no. of units in table 4, to implement into the wall-floor ratio. The internal wall ratio is multiplied by the surface area of the interior walls to find surface area of interior walls. A window-wall ratio is derived with the same approach as the internal wall ratio with use of Reynders (2015). Area of windows are specified as a fraction of the interior walls; therefore, the window-wall ratio is multiplied by the surface area of the interior walls. Surface area of internal and interior walls are thereafter combined. To find resulting output of wall-floor ratio, surface area of the combined walls is divided by the measured surface area of floors derived from table 4. Other references used which give some assertiveness to derive the wall-floor ratio is:

- In Wolisz et al. (2013), three apartment residential houses built in 1964 made of massive brick similar to MFH building typology. Combined interior and internal wall to floor ratio is 1.95, and windows to wall ratio is 0.08 are used (Wolisz et al. 2013).
- In Reynders (2015), to calculate thermal mass of the Belgian residential building sector interior wall ratios of 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 and 2.0 and window to wall ratio of 0, 0.25, 0.5 and 0.75 are used (Reynders 2015).
- In Rønneseth et al. (2019), MFH are modelled with geometrical properties with window/envelope ratios of 0.141, 0.165 and 0.175 (Rønneseth et al. 2019).

The resulting wall-floor ratios used in this thesis is presented in table 5 under:

Table 5: Wall-floor ratio per segment and cohort. Own calculations.

Segment	Cohort	Wall-floor ratio
SFH	-1955	1.644
	1956-1970	1.579
	1971-1980	1.524
	1981-1990	1.213
	1991-2000	1.280
	2001-2010	1.185
	2011-2020	1.115
	2021-	1.115
TH	-1955	1.392
	1956-1970	1.492
	1971-1980	1.506
	1981-1990	1.523
	1991-2000	1.403
	2001-2010	1.398
	2011-2020	1.316
	2021-	1.316
MFH	-1955	1.768
	1956-1970	1.547
	1971-1980	1.540
	1981-1990	1.516
	1991-2000	1.458
	2001-2010	1.419
	2011-2020	1.336
	2021-	1.336

This thesis focusses only on internal mass of a building, which is not exposed to ambient temperature directly. External thermal mass is therefore not considered. Thermal energy storage has been calculated with a single-zone building principle, which means that all rooms in a building is treated the same. This means that the same temperature is the same in all rooms in any given time. Multi-zone buildings are therefore not considered. Contributions to thermal mass from the inside air and from furniture are found in this thesis to only have a minor effect and therefore excluded from the resulting output.

As described earlier, different materials possess dissimilar thermal attributes which effect the total potential of thermal capacity in walls, floors and ceilings. Due to the fact that information about material usage specific for interior materials is not present in literature concerning the Norwegian building stock, the same assumptive-intuitive approach used earlier is used. Only to a certain degree, some references can give some assertiveness about the material usage in the material use of internal partitions concerning some cohorts. References used to determine material type for interior walls, floors and ceilings for each building type and cohort in the building stock is presented as follows:

- In Prognosesenteret (2012), main bearing materials in the Norwegian residential sector concerning statistics from 1996 and 2010 are presented, which give some assertiveness to what kind of material is used as interior floors and ceilings:

Table 6: Main bearing materials in the Norwegian residential building sector. From Prognosesenteret (2012).

Statistics 2010	Wood	Concrete	Light clinker	Steel/other
SFH	83%	7%	7%	2%
TH	78%	11%	5%	6%
MFH	23%	54%	1%	22%
Statistics 1996	Wood	Concrete	Light clinker	Steel/other
SFH	92%	3%	4%	1%
TH	91%	5%	4%	1%
MFH	12%	78%	2%	8%

- Comments about material type usage in all types and cohorts in the Norwegian building stock is listed in the webtool of the project TABULA/EPISCOPE (IWU 2017), though not concerning interior materials.
- Perera et al. (2014) reports that wooden panels are the preferred material in terms of interior walls in most Norwegian residential buildings (Perera et al. 2014).

- In German residential buildings, interior material to inside air used in respective partitions is gypsum for interior wall, concrete as ceiling and massive brick as floor (Wolisz et al. 2013).
- In Polish residential buildings, interior material to inside air used in respective partitions is plaster to interior wall, oak to interior ceiling, terracotta to floor (Knapik 2018).

Looking at the total building stock, in general large variations of interior material use is predicted. However, due to the complexness, the thesis tries to represent the average material usage in different segments and cohorts in the stock. Material type use for interior partitions in the respective building segments and cohorts including rehabilitation states is used in this thesis as follows:

Table 7: Average material interior partition usage in segments, cohorts and refurbishment states in the Norwegian residential building sector (A1 = archetype 1, A2 = archetype 2, A3 = archetype 3). Own settings.

Segment	Cohort	Partition				
		Floor (A1,A2,A3)	Wall (A1)	Wall (A2,A3)	Ceiling (A1)	Ceiling (A2,A3)
SFH	-1955	Floor board	Compact wood	Wood panel	Compact wood	Wood panel
	1956-1970	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	1971-1980	Floor board	Wood panel	Wood panel	Wood panel	Wood panel
	1981-1990	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	1991-2000	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	2001-2010	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	2011-2020	Parquet on concrete	Wood panel	Plaster board	Wood panel	Plaster board
	2021-	Parquet on concrete	Wood panel	Plaster board	Wood panel	Plaster board
TH	-1955	Floor board	Compact wood	Wood panel	Wood panel	Wood panel
	1956-1970	Floor board	Wood panel	Wood panel	Wood panel	Wood panel
	1971-1980	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	1981-1990	Floor board	Wood panel	Wood panel	Wood panel	Wood panel
	1991-2000	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	2001-2010	Parquet on concrete	Wood panel	Wood panel	Wood panel	Wood panel
	2011-2020	Parquet on concrete	Wood panel	Plaster board	Wood panel	Plaster board
	2021-	Parquet on concrete	Wood panel	Plaster board	Wood panel	Plaster board
MFH	-1955	Parquet on concrete	Brick	Wood panel	Concrete	Concrete
	1956-1970	Parquet on concrete	Wood panel	Wood panel	Concrete	Concrete
	1971-1980	Parquet on concrete	Wood panel	Wood panel	Concrete	Concrete
	1981-1990	Parquet on concrete	Wood panel	Wood panel	Concrete	Concrete
	1991-2000	Parquet on concrete	Wood panel	Wood panel	Concrete	Concrete
	2001-2010	Parquet on concrete	Wood panel	Wood panel	Open suspended ceiling under concrete	Open suspended ceiling under concrete
	2011-2020	Parquet on concrete	Wood panel	Plaster board	Open suspended ceiling under concrete	Dense suspended ceiling under concrete
	2021-	Parquet on concrete	Wood panel	Plaster board	Open suspended ceiling under concrete	Dense suspended ceiling under concrete

Finally, to determine the thermal mass of the building stock, effective thermal capacity for interior material is used in this thesis. In Programbyggerne (n.d.), the authors have made some assumptions to determine effective heat capacity. These values are used in this thesis to determine the thermal mass (Programbyggerne n.d.). The values are presented in table 1 or 8 under:

Table 8: Effective heat capacity for chosen constructions. From Programbyggerne (n.d.).

Construction	Effective heat capacity (Wh/m^2K)
"Homogeneous" constructions	
Concrete, thickness> 102 mm	63
Brick, thickness> 81 mm	59
Light clinker, thickness> 64 mm	14
Compact wood (lift / plank); thickness> 39 mm	12
Bonding / joints / ceiling	
Interior cladding: 12 mm plasterboard	2
Interior cladding: 12 mm chipboard	3
Interior cladding: 15 mm wood panel	5
Interior cladding: 21 mm floor board	6
Interior cladding: 22 mm chipboard (floor)	6
Covered heavy constructions	
Thin carpet (5 mm) on concrete deck	38
Thick carpet (10 mm) on concrete deck	19
Parquet (14 mm) on concrete deck	35
"Open" suspended ceiling under concrete deck	30
"Dense" suspended ceiling under concrete deck	10

Effective thermal capacity throughout the whole Norwegian residential building stock is compared to total delivered electricity as space heating per average day in an average month to display an efficiency factor of the different segments analyzed in this thesis.

5.2 Result output

From the period 1960 to 2100 there is calculated TES for all segments, cohorts and refurbishment states. TES is calculated as interior floors, walls and ceilings and is measured in MWh per K. Calculations shows that from 1960 to 2019, available thermal storage has doubled and from 2019 through 2100, available thermal storage will increase with another 8 GWh for a total of 20 GWh/K available at all times for the whole Norwegian building stock. Table 9 shows selected years of available thermal storage in all three types of buildings. In 2020, there are approximately in total 12 GWh/K available as heat storage in the whole Norwegian residential stock.

Table 9: Available effective heat capacity (in MWh/K) for chosen years total and per segment. Own calculations.

Year	SFH (MWh/K)	TH (MWh/K)	MFH (MWh/K)	TOTAL (MWh/K)
2000	5568,99	1122,74	3031,88	9723,62
2020	6154,07	1739,59	4091,39	11985,05
2030	6460,31	2083,08	4935,90	13479,29
2040	6677,22	2378,87	5831,87	14887,96
2050	6774,23	2610,62	6720,28	16105,13
2100	6796,96	3350,16	10247,69	20394,81

Figure 32 shows the contribution of available thermal storage as effective heat capacity per Kelvin from all three types of buildings from 1960 to 2100. The figure shows that SFH is the building type with most available thermal storage up until around 2050, where MFH takes over as the most important building type in terms of available storage. TH has the least amount of thermal storage throughout the whole period. From 1960 to 2000, SFH and TH experiences the most amount of increase with a 94% and a 95% increase. In that same period, MFH records just an increase of 27%. From 2000 to 2050 however, the trend of MFH changes completely. MFH will have an increase of 122% in that period. TH will also experience an increase in the increase rate of 133% from 2000 to 2050. The increase of SFH however stalls. While MFH gain the gap up to 2050 to SFH, the increase rate of SFH in the period will be 21%. From 2050 to 2100, MFH have caught up with SFH and from 2050 MFH will become the most important building type in terms of available thermal storage. While MFH experiences now the highest increase rate of all the three types of buildings with 53% in that period, SFH' progression stalls almost completely. Over that same period SFH, will now have almost the same constant amount of thermal storage available up to 2100. The trend of TH will also experience a drastic change, from a high increasing rate from 2000-2050 to a low increasing rate from 2050-2100 with 28%.

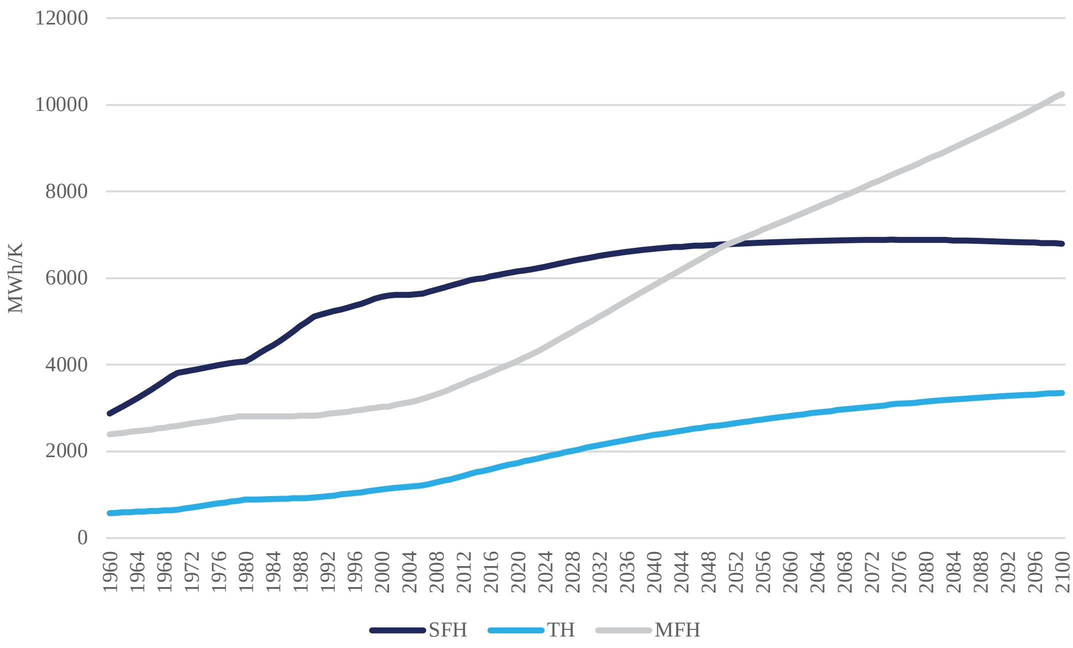


Figure 32: Available effective heat capacity (in MWh/K) per segment in the Norwegian residential building sector. Own calculations.

Figure 33 shows the calculated thermal storage as effective heat capacity per Kelvin divided by “real” estimated delivered electricity as space heating per an average day in January in the period from 1960 to 2100 to display an efficiency factor of the different segments analyzed in this thesis. The figure can be understood by a factor which represents how much thermal storage in all types of buildings is available at all times, considering the amount of electricity demand as space heating is available to use in a future potential scheduled DR event in the different segments in the Norwegian residential building stock. The result output looks at an average January day as an example. Looking at SFH and TH in an average January day, the two segments is showing almost the same trend from 1960 up until around 2035. The two segments, shows a factor between 0.05 and 0.15 in that period. MFH is clearly showing a different trend. This segment shows a large decreasing trend in the efficiency factor from 1960 to 2015. The factor is decreasing from around 1 to 0.29. However, compared to the other types of buildings, MFH shows that the efficiency factor is higher in terms of thermal storage available at all times considering the amount of electricity demand as space heating is available to use in a DR event, compared to the two other mentioned segments throughout the whole period. Because of the “adaptation” factor used by Sandberg (2017), it shows as a jump in terms of the factor but shall be ignored as mentioned earlier. MFH increases from a low point of 0.29 in 2015 to over 1 in 2100, which means that the type of building will reach the same level back in 1960 at around the year 2094. By the latter year, the efficiency will surpass that level. From 2015, the MFH will more than triple the efficiency factor. Looking at SFH from 2035, shows a fairly large increase with also here a triple of the amount of thermal storage available. Looking at TH from 2035, shows a very large increase compared to SFH. The efficiency factor increases almost times seven by 2100 and has almost caught up with the factor of MFH.

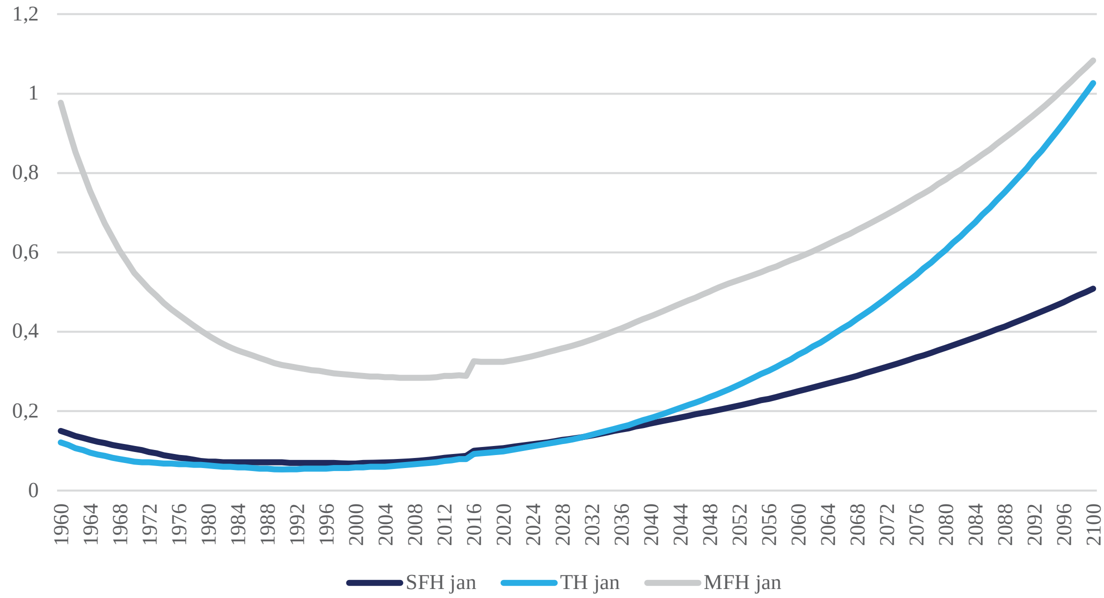


Figure 33: Efficiency factor. Available effective heat capacity (in GWh/K) divided by estimated "real" delivered electricity (in GWh) as space heating per average day in January per segment in the Norwegian residential building sector. From Sandberg (2017) with own calculations.

6 Discussion

In the following chapter, discussion of the thesis will be presented. In the three-parted discussion, integration of DR in Norway, electricity use as space heating and thermal mass is discussed. The following subchapters will present an answer for all research questions that is given in subchapter 1.2.

6.1 Integration of DR in Norway

Following discussion will give answer to following research question: "*What is needed to implement a demand response scheduling program in the Norwegian power market?*".

Vast amounts of hydro power resources in Norway makes the country especially robust in terms of capacity adequacy. However, with larger shares of VRE introduced to the Norwegian power market, the robustness of the market in terms of delivering adequate transmission and generation capacity can potentially be altered. The conducted review of literature in this thesis shows that VRE and especially wind power will be important in the Norwegian and Nordic power market going forward. The potential effect of increased price volatility in the market increases the need for new or existing flexibility. There is large agreement in literature that DR is one of the best solutions as new flexibility integration into the market. However, what kind of new flexibility measure which will be introduced to the power market in the future is uncertain and challenging to predict.

Considering stationary energy use in mainland Norway, the residential building share of two-thirds of total final energy use exemplifies the dominant side the residential sector is energy-wise. Norway is situated in a cold-temperate climate. Throughout a year, the total Norwegian residential building stock requires large amounts of space heating, especially in the winter period and according to the result output in this thesis large amounts of heating is required in future years even though the demand will decrease substantially from 2019. Space heating is the single-most important end-use activity in the Norwegian residential sector, while electricity is the most important energy heating source. The DR potential in the residential sector is found to be higher compared to the industry in Norway and residential heating systems inhibits the largest potential of all end-use in the residential sector. For this reason, DR control of residential electrical space heating as a flexibility measure makes an excellent case.

Main action of DR today is normally disconnection of loads, however not apparent in Norway. If a Norwegian efficient wide-based implementation of DR scheduling programs shall enter the Norwegian power market, numerous challenges and barriers must be tackled. Firstly, a demand for flexibility has to be in place. With other flexibility measures entering the stage, DR must compete with these measures within a cost-efficient manner. Implementation of one type of flexibility measure will lead to decreasing profitability for other flexibility measures. Therefore, measures that is introduced first will have some advantages. An example is scale effects which will lead to a competitive advantage in the market. How many households that will receive and use real-time price information and participate in a potential DR scheduled load shifting program will inflict the development of DR. The quantity that aggregator services or network companies inflict on end-users to shift their load in peak hours will also define the development of DR. There are various factors that affect the performance of DR in an event. Volume, duration, response, recovery and reliability. A single indicator to indicate performance of flexibility of a measure may be inaccurate. At present time, the market is customized to favor flexibility from producers. Existing barriers that hinders the integration of DR in Norway are:

- Real-time pricing and metering. Consumers and/or aggregator services will not be able to respond fast and correctly without real-time pricing and metering, because few people have the opportunity to follow spot prices hour-by-hour. However, with smart meters a part of the residential sector today this has potential to change. If the system is not precisely designed, it can ill inform consumers and it can be challenging for consumers to deal with many actors at the same time. The information share between actors in a market will lead to data security and privacy questions. DR implementation will also lead to minor customer savings. Some customers who participate in a DR program may be disappointed because of minor savings, because DR is mostly not implemented because of the economic savings. However, some customers may be eager to quit programs because of this. It is important to mention that smart meters and real-time pricing are not enough to optimize the integration of DR.
- Market for aggregator services. Without aggregator services, consumers are not able to deliver efficient management of their loads and can potentially alter the development of DR and may lead to failure. There is also challenges regarding adapting to regulations that give access to aggregators. The market inhibits actors with different attentions and interests.
- ICT and automation. Without ICT and automation, the system will not be able to add accuracy to real-time pricing and operation of DR in the market.
- Settlement period and bid size. The settlement period is too long to implement accurately reactionary DR programs. The bid size is too large for smaller participants,

which exclude them from the operation in the market. This leads to exclusion of many residential customers.

Following part will present possibilities and advantages with DR. Integration of real-time pricing and metering, aggregator services, ICT and automation and lower bid sizes may lead to better allocation of resources and decreased grid investments in the system. As smart meters have entered the stage in the Norwegian as well as the Nordic power market, the road to implementing a fully operational DR scheduling program has been shortened. Smart meters and microgrids will enhance price signals in real-time. With smart meters, it can facilitate introduction of time-varying prices while it can also facilitate direct load control of appliances with aggregator services and it can overcome information asymmetry and provide other important consumption information. Aggregator services can increase the efficiency of the operation of DR. While digitalization and automatization will be increasingly important in the Norwegian power market in the future going forward, DR will be easier to operate with three-side communication between producers, operators and consumers. Increased interconnection means that the North European integrated power market can become increasingly more flexible. A push of some of the regulating power from generators to consumers will be "healthy" for the power market. With increasingly more efficient segments of the building stock, the average U-value will decrease. This should increase possibility of DR as time span of shifting will increase. However, as discussed earlier power rating of heating will be lower for these buildings and will thus have a reduced effect on the amount of available load shifting. One important advantage that favor DR as the new needed flexibility integrated into the Norwegian power market is that households in Norway is situated everywhere. Even areas which is secluded. These areas, even though wind power can be an important energy source in these areas can have some trouble to deliver adequate capacity, which means that there is higher risk of shortages in some areas. Wind power is variable which makes these areas more vulnerable in terms of covering power needs. DR can potentially act as an important source to these areas and increase capacity adequacy. Literature predicts that small and cheap new flexibility will be introduced earlier to the market than large and capital-intensive investments. DR makes an excellent argument regarding early integration concerning latter remark, since DR is a cheap option to shift load in time. However, the economic system in terms of taxes and tariffs and political decisions has a great infliction of what will come next. Load shifting is ideal in terms of integration of flexibility because the continuity and quality of the measure is not altered.

6.2 Electricity use as space heating

Following discussion will give answer to following research question: *“What is the maximum load shifting potential per segment in the Norwegian residential building stock in the period 1960 through 2100 concerning electrical heating in residential buildings in a demand response event?”*.

According to the review of literature conducted in this thesis, an average 70-80% of Norwegian households is electrically heated in comparison of 50% in Sweden. As discussed in 6.1, space heating offers the highest potential of all end-use activities in the residential sector in terms of DR. In the literature review in chapter 2.2 according to different references, DR potential in the residential sector in Norway in terms of load shifting is found to be 1-3 GW (Gaia 2011), 5.9 GW (Gils 2014) and 4.1 GW but with an economical potential of 1.8 GW (Kringstad et al. 2018). The modeling carried out in this thesis shows roughly the same amount of potential of what is found in Gaia (2011) and Kringstad et al. (2018). Due to this, Gils (2014) may inhibit implications of overestimation. The potential of maximum load shifting in a DR event is found to be 3.67 GW today (2019), however taken into account that the potential will probably not be achievable, the economic maximum potential of load shifting in a DR event will roughly be around 1.61 GW, using the economic share method of Kringstad et al. (2018). By comparison the total rated capacity of Norwegian wind power is currently roughly around 1.7 GW (2018), but will increase with 1 GW extra in 2019 (Vindportalen 2018). Considering the amount, load shifting potential in Norway can have a significant effect on the overall load curve and can provide new needed flexibility. However, the potential will decrease in time to 3.25 GW in 2030 and 2.34 GW in 2050. In 2100, the estimate is decreased to 1.09 GW of load shifting. The load shifting potential can be provided in a scheduled timeframe of some minutes or hours. In accordance with Kringstad et al. (2018), the maximum space heating potential in hours (with 2019 numbers) as a function of time will decrease to 3.5 GW after half-an-hour, 3.3 GW after one hour and 1.8-2 GW after two hours. The result output of the analysis of electricity use as space heating is summarized in table 10.

Table 10: Summarized result output of analysis of electricity use as space heating.

Year	Segment			Total
	SFH	TH	MFH	
Estimated “real” delivered electricity as space heating, scenario baseline (in TWh)				
2019	11.9	3.5	2.5	17.9
2050	6.7	2.1	2.6	11.4
Estimated “real” delivered electricity as space heating per day in January, scenario baseline (in GWh)				
2019	58.2	17.5	12.6	88.1
2050	32.8	10.4	13	56.2
Estimated “real” load shifting potential in January (in GW)				
2019	2.43	0.73	0.52	3.7
2050	1.37	0.43	0.54	2.3

It is very important to remember that the result outputs are largely uncertain far back and forward in time, especially after 2050. The method applied after 2050 leads to large uncertainties in the model in this timeframe. Therefore, table 10 is intuitively showing only estimates for 2050 in the future. It is interesting to recognize that the MFH segment of the Norwegian residential building stock is increasing by time in terms of delivered electricity as space heating and load shifting potential, while clearly the two other segments, SFH and TH is decreasing. One of the most prominent factors is due to that larger shares of the population moves to urban areas with more apartment blocks. Which segment, cohort or archetype which is analyzed in the Norwegian residential building stock is important in terms of how much energy the different parts consume. Old, not renovated buildings is found to be the buildings that use the most energy. While dwellings in MFH is generally using less amount of energy with average use of 10 MWh per dwelling per year (before year 2005), dwellings in for example SFH use an average 25 MWh per dwelling per year. Larger shares of the population moving into the MFH segment which has less living space per person leads to a decline in total usable area and will eventually lead to a decreasing trend of energy use and thereby decreased delivered electricity as space heating in the overall Norwegian residential building stock. The SFH and TH segments is calculated to decrease in time according to table 10. An important factor is that while the dwellings in the segments are being renovated or new buildings along with stricter technical building regulations are constructed, the segments becomes increasingly more energy efficient. Along with a flattening of the segment of SFH, this materializes in an overall decrease in the two segments. While TH’ total floor area increases in time, the increasing energy efficiency factor makes up for the increase. Dwellings in the MFH segment will also experience averaged increased energy efficiency. However, the projected increase of the population moving into MFH dwellings makes up for the increase in energy efficiency. Usage of HP will play a role in the Norwegian residential building stock moving forward. HP which is known for its efficiency will change the future of the energy demand in the stock. However, projection of usage rate is difficult to interpret and therefore the prediction of total energy use in the stock is difficult to calculate and thus becomes uncertain. Local production with solar PV in residential buildings may also inflict the total demand in the future.

By use of the load shifting principle, shifting to an alternative type of energy source will also be possible. Especially biomass which is used frequently along with direct electrical space heating. However, it is important to recognize that heating with wood is more common in the SFH segment and is largely uncommon in the MFH segment, which means that shifting to an alternative type of energy source when the need of flexibility in a DR scheduled event arrives is best suited for the SFH segment.

6.2.1 Simplifications, assumptions and limitations of the analysis

- Many input parameter values in any residential building stock energy model is uncertain going back and forward in time.
- The building stock model is not able to capture short-term stock changes and the energy model is not able to capture short-term energy use changes. It is important to also know that the models are not meant to capture the short-term changes anyway, but it is important to remember it when interpreting the result outputs. As Sandberg (2017) argues, modelling of short-term development requires other input parameters reflecting for example the economic or political situation.
- The post-war construction boom is not fully captured by the building stock model, expressed by Sandberg (2017), and in the recent period of low construction activity, this activity is overestimated in the model. This makes the age composition of the simulated current and future stock somewhat skewed.
- Energy need intensities applied in the building stock model are taken from the Norwegian residential building typology in the IEE project EPISCOPE.
- There is a discontinuity/jump in the results on delivered electricity as space heating between 2015 and 2016, due to different adaptation factors applied in the historical and future analyses. Sandberg (2017) argues that the choice of adaptation factor is important as it influences the simulated thermal energy demand directly.

6.3 Thermal mass

Following discussion will give answer to following research question: *"How will the potential of thermal mass capacity change over time in different segments of the Norwegian residential building stock?"*.

In accordance with the material use in different partitions in the segments in the Norwegian residential building stock, table 7 shows that the three segments use generally wood panels or plaster boards as the material for interior walls, which is also the case for interior ceilings in the segments SFH and TH. However, in MFH, the most usable material in interior ceilings is concrete. Parquet is the most used material for internal floors in all three segments. The conclusion that can be drawn from this is that the MFH segment inhibits larger average potential in thermal energy storage per dwelling because of the significant use of concrete in the segment. Concrete is found to have a much larger potential in terms of effective heat capacity than wood panels and plaster boards. The extensive use of wood panels and plaster boards in the segments SFH and TH leads to a lower potential in these. Total population living in the different segments also inflicts the total potential of effective heat capacity. The SFH development increase in terms of total floor area will eventually stagnate and this effect will inflict the thermal energy storage potential. The increase in effective heat capacity in SFH will stagnate in the same timeframe as the total floor area development. While TH inhibits less potential compared to the two other segments, the segment will increase more than what SFH will after 2019, due to the increase in total floor area. The MFH segment stands out with its large increase of effective heat capacity after 2019. Not only is the large use of concrete in the partitions affecting the outcome, the large increase in total floor area due to the larger share of the population moving into apartment blocks also affect the output. The result output of the analysis of thermal mass is summarized in table 11, with assumed uniform air temperatures.

Table 11: Summarized result output of analysis of thermal mass.

Year	Segment			Total
	SFH	TH	MFH	
Available effective heat capacity (in GWh/K)				
2020	6.1	1.7	4.1	11.9
2050	6.8	2.6	6.7	16.1

It is also here very important to remember that the result outputs are largely uncertain far back and forward in time, especially after 2050. Therefore, table 11 is intuitively showing only estimates for 2050 in the future. When discussing the potential of thermal energy storage, bear in mind that the result output of table 11 shows only the maximum potential. The realistic potential will be smaller due to the principle of TES described in figure 6 of a “power node”. The potential will also generally be lower due to economic factors. Most of the economic potential has a time period of less than three hours. The potential is also determined by the temperature settings in the dwelling. As higher the setting of temperature space heating increase is set in a dwelling, the larger the potential of potential thermal energy storage will increase. If the temperature is set to increase 2 degrees in a dwelling, the potential can maximum potentially double. Heat losses in the form of transmission and ventilation will affect the result output. Roughly summed average heat transfer coefficient per segment in the Norwegian residential building stock in terms of ventilation and transmission leads to average estimated total heat loss for each dwelling to be 275.8 W/K (SFH), 361.7 W/K (TH) and 1873.5 W/K (MFH), however in the different segments large variations will occur. When the cohorts in the different segments become increasingly more energy efficient due to renovation and construction of new buildings, a decrease of heat losses will occur which eventually will lead to an overall decreasing trend of heat losses through time. The result output visualized in figure 33 shows that the MFH segment is the most efficient segment of the three segments analyzed throughout the whole analyzing timeframe. This is mostly due to the high usage of concrete including the high increase of total floor area after 2019. When considering figure 33, it is important to remember that the estimated “real” delivered electricity as space heating per an average day in January which acts as the denominator in the estimated efficiency factor is largely determined by total floor area in the respective segments. The efficiency factor is determined by effective heat capacity in respective segments and the mentioned delivered electricity share. Therefore, a lot of factors play a role determining the efficiency of the respective segments.

Using TES in a scheduled DR event is found to be a promising, efficient and economically viable technology and it enables wide spread integration of efficient VRE generation. Utilizing TES is promising in Norway because Norwegian residential buildings are generally satisfyingly insulated and high electricity usage in the cold-temperate climate of Norway allows large volumes of thermal mass to be utilized. The large load shifting potential found in the analysis of electrical space heating allows TES to be utilized efficiently in the building stock. This analysis is meant to “open up” about a minor studied field in Norway and to identify the potential of thermal mass usage in DR programs.

6.3.1 *Simplifications, assumptions and limitations of the analysis*

- Lack of qualitative statistical data of the building stock requires assumptions about material usage and thermal properties of the materials including ratios as for example wall compositions of different segments. A theoretical assumptive intuitive rule of thumb approach has been applied to find the material usage and the respective ratios for the different segments, which is a strong simplification of the “real” output. A drawback is that the potential has been quantified with a single parameter including that with a single parameter there is not accounted for unheated spaces, day and night zones and solar and internal gains. Infiltration losses are not considered.
- The applied thermal mass principle with effective thermal capacity is a simplistic approach to calculate the thermal mass potential. Thermal capacities and thermal behavior are dependent on large variational conditions in different segments and cohorts, which is difficult to compute without engineering models. Engineering modeling of thermal properties and thermal behavior in different segments and cohorts of the building stock will be more detailed but requires a largely complex model.

7 Conclusion and further work

The research of the thesis has been conducted with review of literature and analyses of electrical space heating and thermal mass. The thesis has attempted to answer following research questions:

- *What is needed to implement a demand response scheduling program in the Norwegian power market?*

  Implementation of DR in the Norwegian power market is found to be challenging, but possible. Firstly, a demand for flexibility must exist in the first place. DR must compete with other flexibility measures within a cost-efficient manner. Real-time pricing and metering are found to be the key enablers of a "kick-off" of DR in Norway. However, other factors like a market for aggregator services, ICT and automation, shorter settlement period and lower bid sizes is also significantly important to apply before DR can become efficient.
- *What is the maximum load shifting potential per segment in the Norwegian residential building stock in the period 1960 through 2100 concerning electrical heating in residential buildings in a demand response event?*

  The maximum load shifting potential in a January month for SFH is found to be 2.43 GW in 2019 but decreasing to 1.37 GW in 2050. For TH, the potential is found to be 0.73 in 2019 but decreasing to 0.43 in 2050. For MFH, the potential is found to be 0.52 GW in 2019 but slightly increasing to 0.54 GW in 2050.
- *How will the potential of effective heat capacity change over time in different segments of the Norwegian residential building stock?*

  The potential of effective heat capacity in SFH is found to be increasing from 6.1 GWh/K in 2020 to 6.8 GWh/K in 2050. For TH, the potential is found to be increasing from 1.7 GWh/K in 2020 to 2.6 GWh/K in 2050. For MFH, the potential is found to be increasing from 4.1 GWh/K in 2020 to 6.7 GWh/K in 2050.

Large potential of DR is found to exist in terms of load shifting, however overall potential will decrease with time. Using TES in a scheduled DR event is found to be a promising, efficient and economically viable technology. To compute more precise result outputs, using qualitative and quantitative data containing the Norwegian residential building stock of different factors and parameters affecting the performance of DR with the thermal energy storage principle should be modelled. Based on the findings of this work and consideration of simplifications and assumptions made in this thesis, this paragraph summarizes suggestions for future research:

- Construct a Norwegian national database for what kind of material is used for different cohorts in the building stock in terms of the envelope and interior cladding.
- Construct a Norwegian national database for effective heat capacity for all materials used in different cohorts quantified in segments in the building stock in terms of the envelope and interior cladding including air and furniture.
- Modelling and usage of Grey-Box modelling with Model Predictive Control schemes with utilization of TES in Norwegian DR scheduling programs.
- Construct engineering modeling of thermal behavior for all segments and cohorts in the Norwegian residential building stock.
- Multi zone building models should be constructed for the Norwegian residential building stock, where the heat demand may differ significantly between zones. This means applying night and day zones, where night zones are not in use at day time and day zones are not in use at night time.

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Appendix

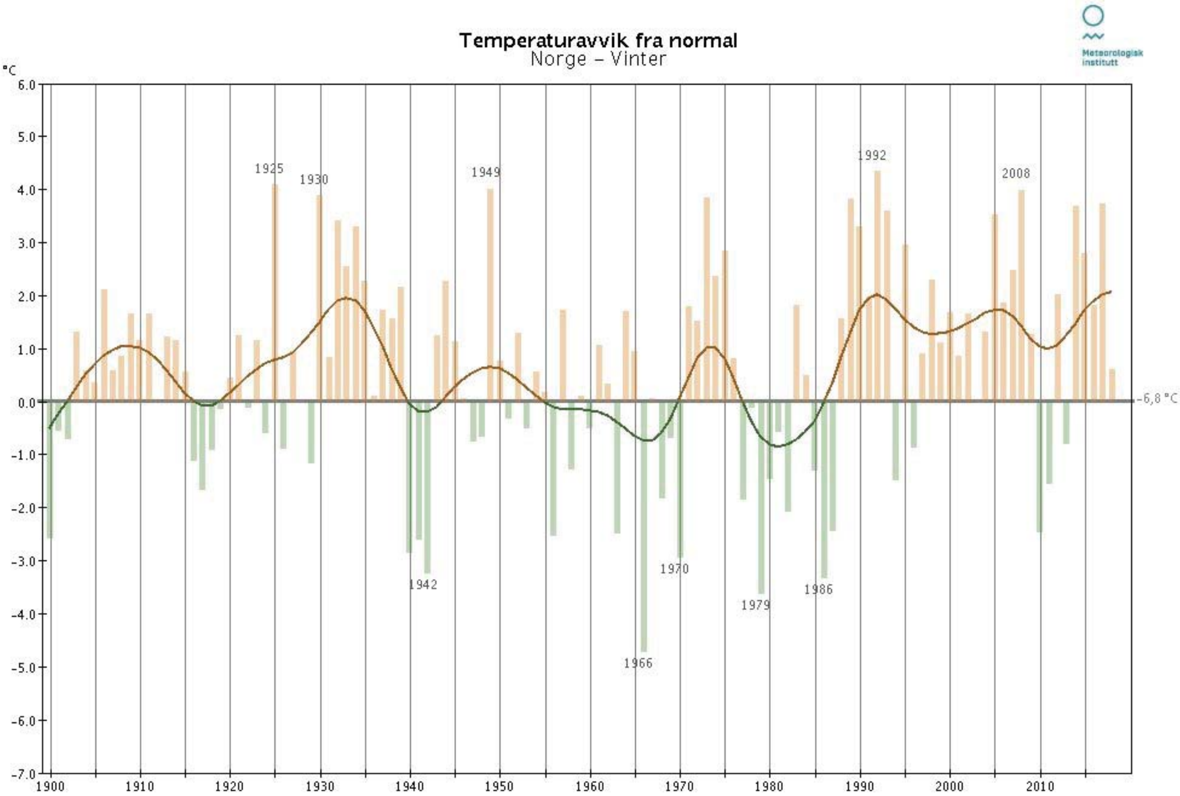
Appendix 1

Technical thermal mass properties of different building materials used in the Norwegian residential building sector. Extracted from (Programbyggerne n.d.).

	Thermal conductivity	*Density*	*Heat Capacity*	*Thermal diffusivity*	*Equated thickness*
Insulation materials	λ (W/mK)	ρ (kg/m³)	c (Wh/kgK)	α (m²/h)	δ (m)
Mineral wool class 36	0,036	40	0,23	0,0039	0,122
Mineral wool class 39	0,039	40	0,23	0,0042	0,127
Mineral wool groundplate	0,045	80	0,23	0,0024	0,096
Expanding polyester	0,036	40	0,3	0,003	0,107
Expanded polyester in the base	0,05	40	0,3	0,0041	0,126
Extruded polyester	0,03	30	0,25	0,004	0,123
Polyurethane	0,027	30	0,25	0,0036	0,117
Cellulose fiber	0,039	40	0,23	0,0042	0,127
Cork	0,045	150	0,5	0,0006	0,048
Wood and plate materials					
Pine/spruce	0,12	500	0,61	0,0004	0,039
Oak, beech	0,14	700	0,63	0,0003	0,034
Parquet (section)	0,13	600	0,6	0,0004	0,037
Flake	0,12	700	0,36	0,0005	0,043
Plywood	0,14	800	0,33	0,0005	0,045
Plasterboard	0,17	800	0,23	0,0009	0,059
Fiberboard, hard	0,13	1000	0,35	0,0004	0,038
Fiberboard, semihard	0,08	700	0,35	0,0003	0,035
Fiberboard, porous	0,05	300	0,35	0,0005	0,043
Masonry					
Concrete	1,7	2300	0,27	0,0027	0,102
Brick wall	0,75	1800	0,24	0,0017	0,081
Light brick (poroton)	0,3	1350	0,25	0,0009	0,058
Light clinker (Leca)	0,23	800	0,27	0,0011	0,064
Gas concrete (Ytong)	0,12	400	0,27	0,0011	0,065
Clinker tiles	0,75	1800	0,24	0,0011	0,081
Ceramic tiles	0,6	1 400	0,25	0,0017	0,081
Metals					
Steel	50000	7900	0,14	0,045	0,415
Aluminium	220000	2700	0,23	0,354	1,161
Copper	380000	8900	0,13	0,328	1,118
PVC floor covering	0,2	1200	0,28	0,0006	0,048

Appendix 2

Temperature deviation in the winter months in Norway from 1900 to present time (in Celsius). Extracted from (MET 2019).



Appendix 3

Average HDD for Norway calculated for average value in each month in the period 2010-2018 (Hansen 2018).

Year	*Average HDD*
January	626,5
February	545,9
March	510,3
April	375,1
May	230,7
June	132,2
July	69,4
August	95,1
September	175,4
October	332,9

Appendix 4

Physical properties, heat transfer coefficients and energy ware for space heating for the Norwegian residential building stock. Extracted from Tabula WebTool (IWU 2017).

Type	*Rehabilitation*	*Example floor area*	*Heat transfer coefficient by transmission*	*Heat transfer coefficient by ventilation*	*Energyware for space heating*
SFH		(m^2)	H_{tr} (W/K)	H_{ve} (W/K)	El (%)
-1955	V1	254	424	173	0,8
	V2	254	281	130	0,9
	V3	254	161	108	0,8
1956-1970	V1	228	377	155	0,8
	V2	228	276	116	0,9
	V3	228	211	97	0,8
1971-1980	V1	152	183	103	0,8
	V2	152	139	78	0,9
	V3	152	91	65	0,8
1981-1990	V1	123	203	84	0,8
	V2	123	148	63	0,9
	V3	123	114	52	0,8
1991-2000	V1	159	149	108	0,9
	V2	159	138	81	0,9
	V3	159	112	68	0,8
2001-2010	V1	322	92	164	0,9
	V2	322	171	164	0,9
	V3	322	122	137	0,8
2011-	V1	184	99	94	0,9
	V2	184	60	70	0,9
	V3	184	60	70	0,8

Appendix 5

Physical properties, heat transfer coefficients and energy ware for space heating for the Norwegian residential building stock. Extracted from Tabula WebTool (IWU 2017).

Type	*Rehabilitation*	*Example floor area*	*Heat transfer coefficient by transmission*	*Heat transfer coefficient by ventilation*	*Energyware for space heating*
TH		(m^2)	H_{tr} (W/K)	H_{ve} (W/K)	El (%)
-1955	V1	216	477	147	0,8
	V2	216	252	110	0,9
	V3	216	133	92	0,8
1956-1970	V1	297	371	202	0,8
	V2	297	282	151	0,9
	V3	297	203	126	0,8
1971-1980	V1	474	593	322	0,8
	V2	474	440	242	0,9
	V3	474	310	201	0,8
1981-1990	V1	226	212	154	0,8
	V2	226	185	115	0,9
	V3	226	135	96	0,8
1991-2000	V1	202	199	137	0,9
	V2	202	165	103	0,9
	V3	202	132	86	0,8
2001-2010	V1	206	156	105	0,9
	V2	206	152	105	0,9
	V3	206	118	88	0,8
2011-	V1	198	111	101	0,9
	V2	198	67	76	0,9
	V3	198	67	76	0,8

Appendix 6

Physical properties, heat transfer coefficients and energy ware for space heating for the Norwegian residential building stock. Extracted from Tabula WebTool (IWU 2017).

Type	*Rehabilitation*	*Example floor area*	*Heat transfer coefficient by transmission*	*Heat transfer coefficient by ventilation*	*Energyware for space heating*
MFH		(m^2)	H_{tr} (W/K)	H_{ve} (W/K)	El (%)
-1955	V1	1201	1448	613	0,9
	V2	1201	824	613	0,95
	V3	1201	558	510	1
1956-1970	V1	1526	2034	778	1
	V2	1526	1268	778	1
	V3	1526	909	649	0,9
1971-1980	V1	3380	3018	1724	1
	V2	3380	1847	1724	1
	V3	3380	1340	1436	1
1981-1990	V1	1824	1230	930	1
	V2	1824	999	930	1
	V3	1824	752	775	1
1991-2000	V1	1656	1220	845	1
	V2	1656	895	845	1
	V3	1656	672	704	1
2001-2010	V1	1065	337	543	1
	V2	1065	578	543	1
	V3	1065	448	453	1
2011-	V1	1608	779	820	DH
	V2	1608	372	615	DH
	V3	1608	372	615	DH

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